

Tevatron combined Single Top production cross sections

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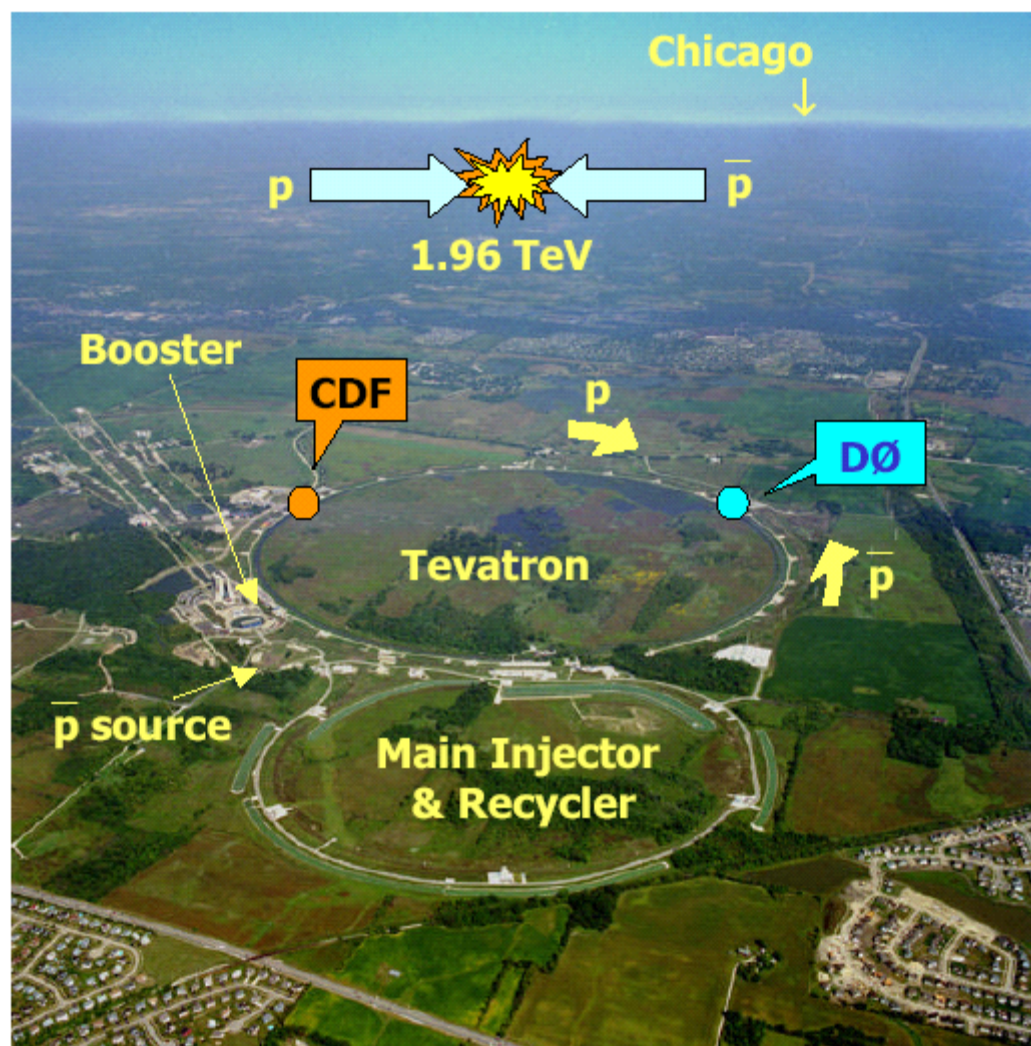


on behalf of the CDF and DØ Collaborations

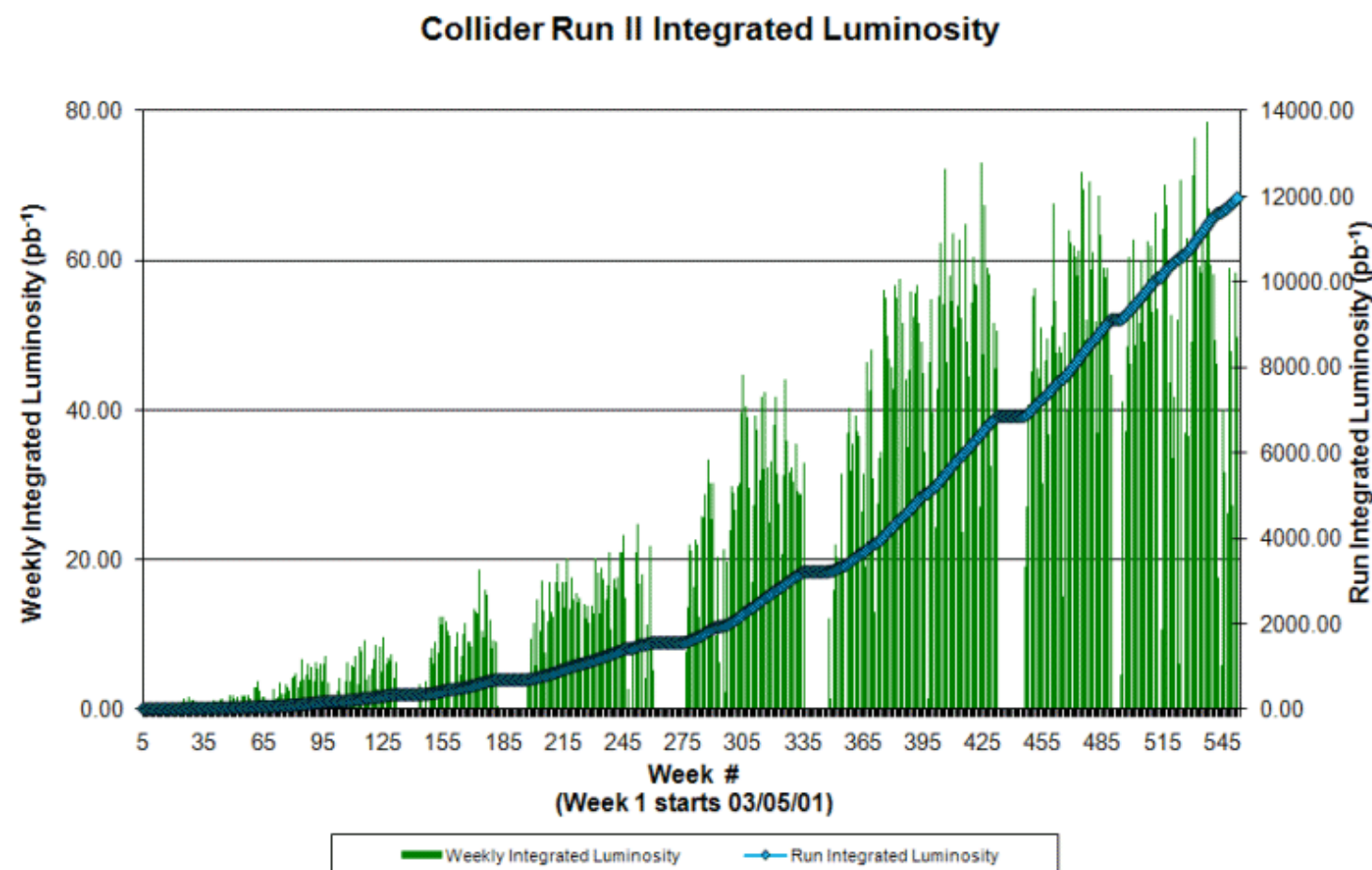
EPS-HEP 2015, Vienna, Austria



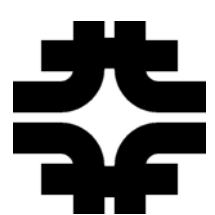
The Tevatron, CDF and DØ



- Run II: $\sqrt{s} = 1.96$ TeV
- In operation from 2002 to September 30th, 2011 (Shutdown)
- Total integrated Luminosity delivered by Tevatron: $\sim 12 \text{ fb}^{-1}$
- CDF & DØ luminosity acquired $\sim 10 \text{ fb}^{-1}$ (full dataset)
- Instantaneous luminosity record: $\approx 4.03 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

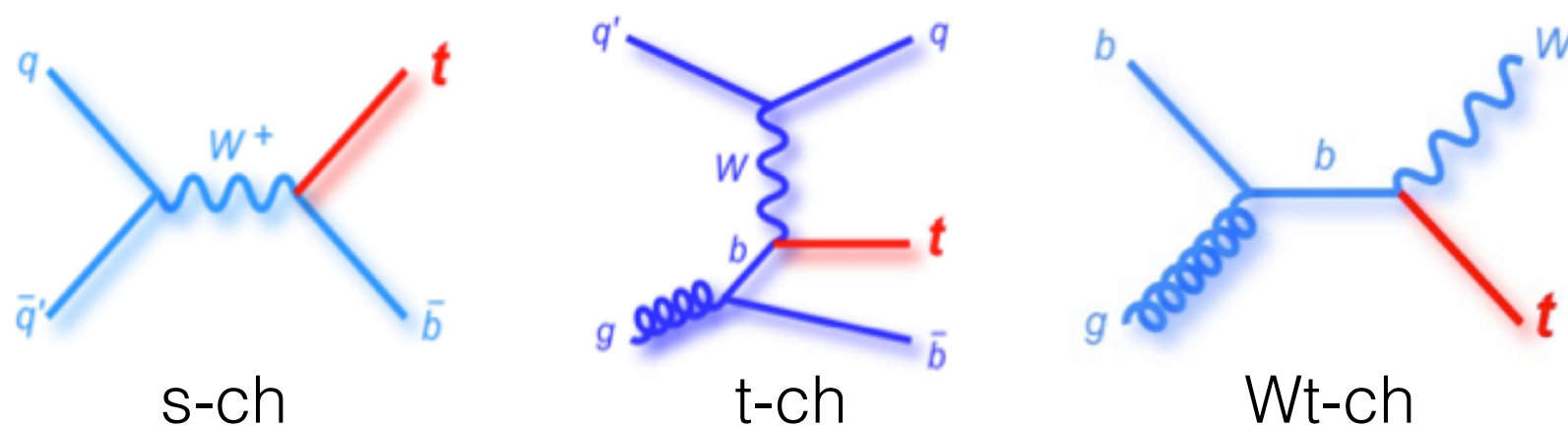


Top quark observed at Tevatron in 1995, by CDF & DØ

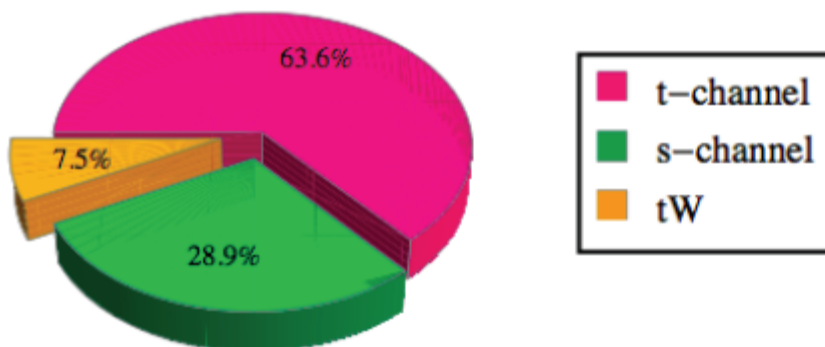


Single Top at Tevatron

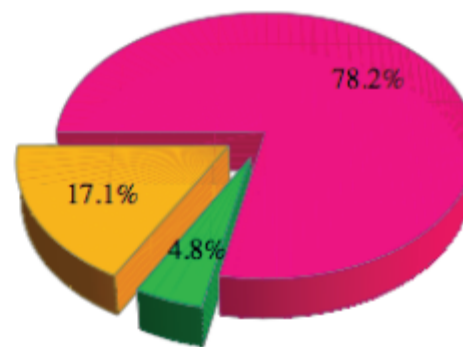
- Production via EW in 3 channels: s, t, Wt;
- First Observation by CDF & D0 in 2009;
Phys.Rev. Lett., 103:092002, 2009;
- Tevatron and LHC both sensitive to t-ch; Tevatron not sensitive to Wt-ch but advantage on s-ch!
at LHC 5 times more signal but 15 times more background....
will be very challenging also at RunII since processes like $t\bar{t}$ increase more than s-ch production!



Tevatron: $\sigma_{\text{tot}} = 3 \text{ pb}$



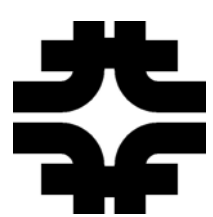
LHC: $\sigma_{\text{tot}} = 114 \text{ pb @ 8 TeV}$



Detector/ $\sigma(pb)$	s-ch	t-ch	Wt-ch
Tevatron (1.96 TeV) ^a	1.05	2.10	0.25
LHC (8 TeV) ^b	5.65	86.5	22
LHC (13 TeV) ^b	11.17	218	70.4

^a : arXiv:1311.0283

^b : arXiv:1506.04072



Motivations

$$\sigma_{\text{single top}} \propto |V_{tb}|^2$$

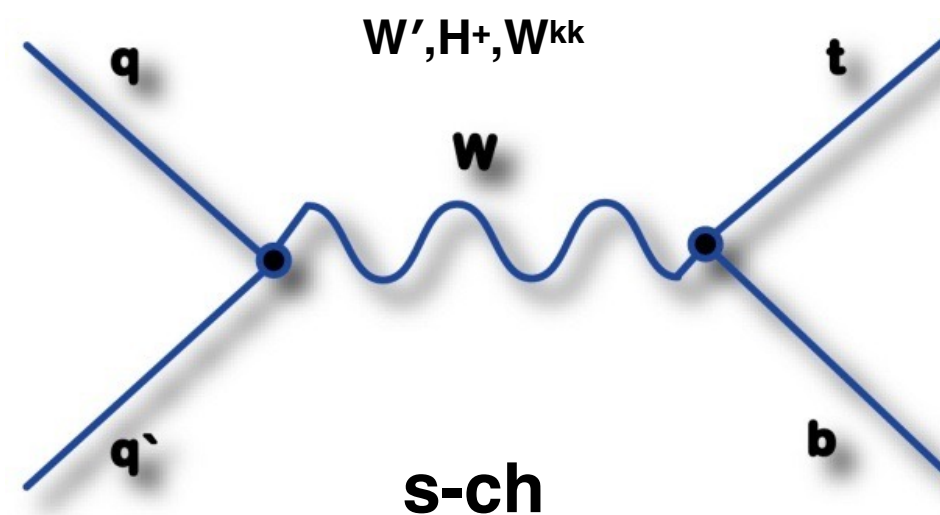
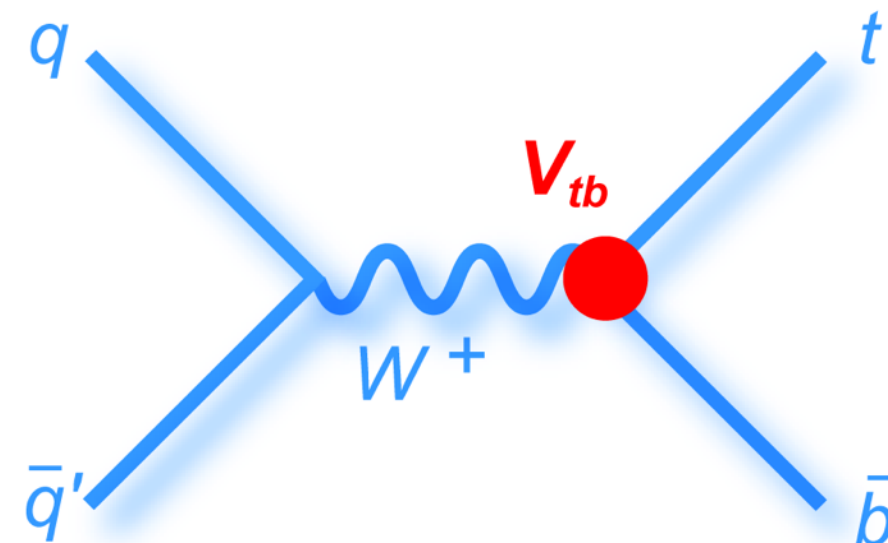
- Direct measurement of $|V_{tb}|$ CKM matrix element;
- Does unitarity holds?

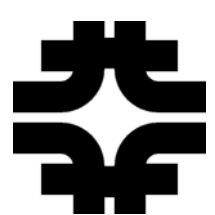
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

Sensitivity to new physics

- t-ch: FCNC
- s-ch: heavy W' , Top pion





Event Selection and Strategy

1) l+jets

- One high- p_T isolated lepton (e, mu)
- Missing transverse energy \cancel{E}_T
- 2 or 3 jets
- At least one b-tag

2) Met+jets (CDF only!)

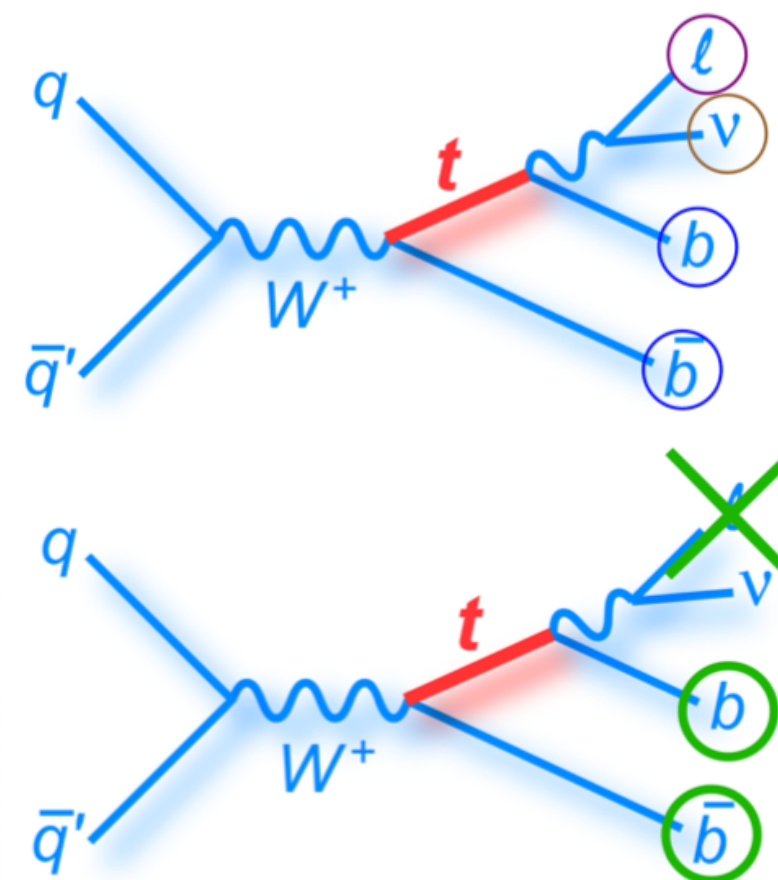
- No isolated lepton (e, mu)
 - ➔ Leptons vetoed, orthogonal to l+jets
- Large MET > 35 GeV
- 2 or 3 jets
- At least one b-tag

Orthogonal Event Selections: (2) adds 33% acceptance to (1)

Multivariate Analysis

The background uncertainty is larger than the predicted signal

- ➔ cannot do a simple counting experiment
- ➔ use of Multivariate Techniques (BDT, NN, ME)



Category	TT+TL	1T+LL
$t\bar{t}$	357 ± 40	560 ± 57
Diboson	58.7 ± 7.8	279 ± 34
Higgs	12.5 ± 1.0	12.0 ± 0.9
Z+jets	31.6 ± 3.5	190 ± 21
QCD	76 ± 31	326 ± 130
W+HF	712 ± 286	2597 ± 1046
W+LF	66 ± 14	1220 ± 175
t-channel	53.4 ± 6.7	265 ± 30
s-channel	116 ± 12	127 ± 12
Total	1484 ± 403	5574 ± 1501
Data	1231	5338

CDF l ν bb Event Yield



DØ Single Top Analysis

Strategy

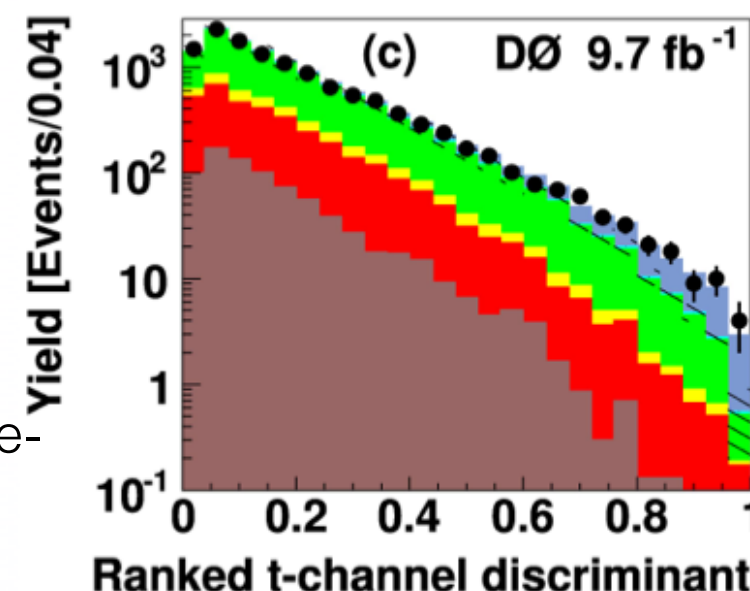
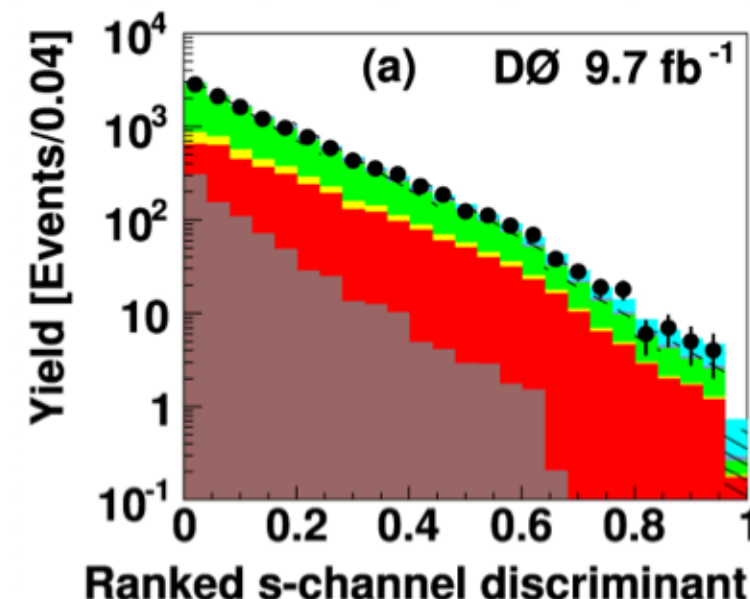
- One analysis in l+jets doing everything with 9.7 fb^{-1} of DØ data
 - s-channel, t-channel, s+t channel measurements
- DØ used three different techniques: BDT, BNN, ME
 - Each method selects different event kinematics → Around 75% correlation

s+t cross section

- Combination of the 3 MVAs in a BayesianNN
- 1D posterior obtained for σ_{s+t} integrating over σ_t with no assumption on SM σ_s/σ_t

$$\sigma_{s+t} = 4.11^{+0.60}_{-0.55} \text{ pb } (\pm 14\%)$$

$$|V_{tb}| > 0.92 \text{ at } 95\% \text{ CL}$$



s-ch VS t-ch cross section

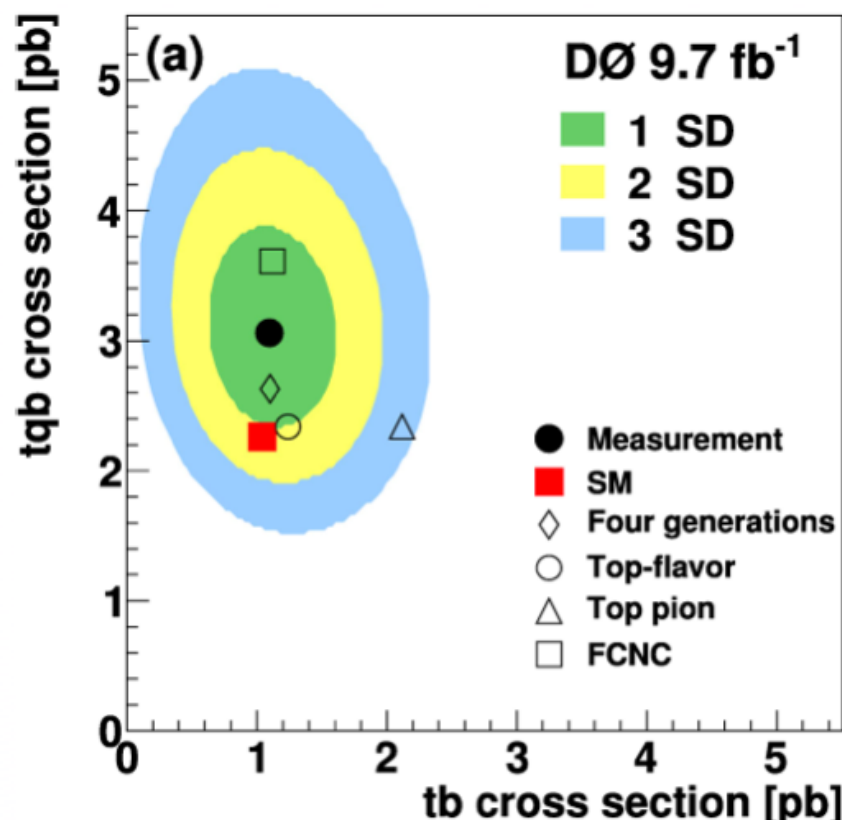
- 2D final discriminant sensitive to s-, t-ch
- Integrating over σ_t and extract σ_s and vice-versa

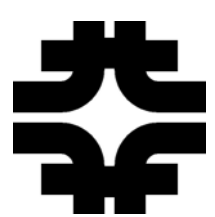
$$\sigma_s = 1.10^{+0.33}_{-0.31} \text{ pb } (\pm 29\%)$$

$$\sigma_t = 3.07^{+0.54}_{-0.49} \text{ pb } (\pm 17\%)$$

first 3.7σ evidence

PLB 726, 656 (2013)





CDF $s+t$ Analyses

Lepton+jets with $L = 7.5 \text{ fb}^{-1}$

- NNs trained with 11-14 variables
- First inclusive measurement with Wt-ch at CDF!

PRL 113, 261804 (2014)

MET+jets with full CDF dataset 9.5 fb^{-1}

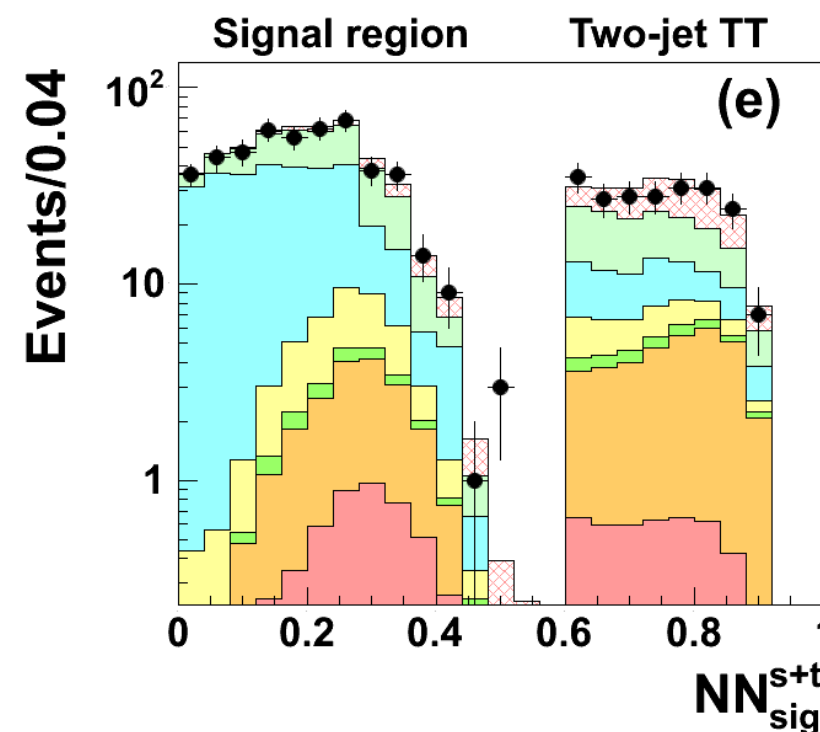
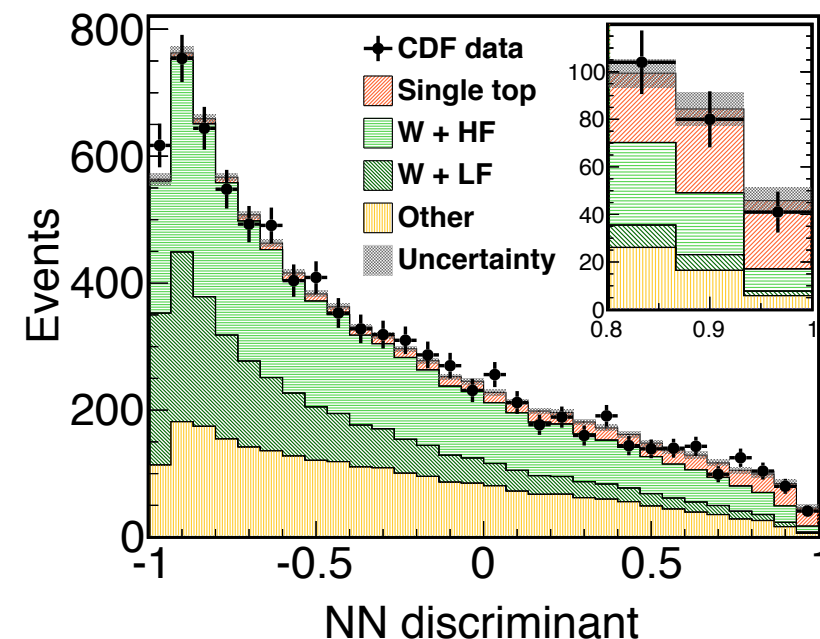
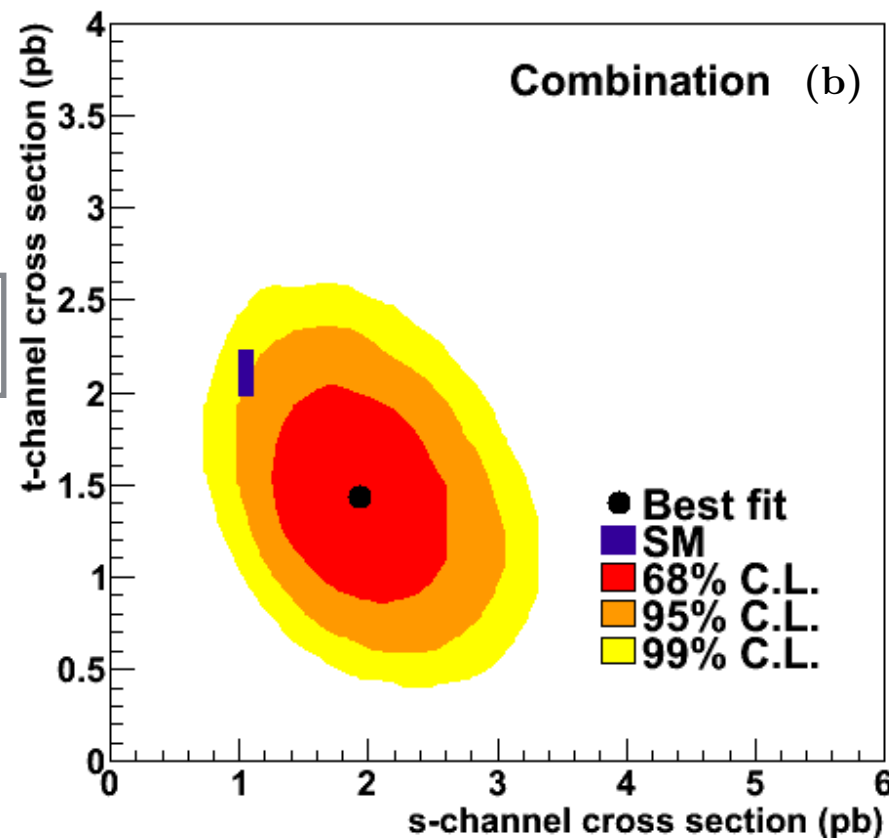
- Completely orthogonal dataset to ℓ +jets selection
- Dedicated NN used to discriminate QCD, V+jets and $t\bar{t}$

CDF $s+t$ Combination

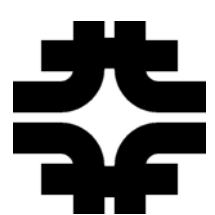
The results of the two $s+t$ analyses (ℓ +jets and MET+jets) are combined by taking the product of their likelihoods and simultaneously varying correlated uncertainties

$$\sigma_{s+t} = 3.02^{+0.49}_{-0.48} \text{ pb } (\pm 16\%)$$

$$|V_{tb}| > 0.84 \text{ at } 95\% \text{ C.L.}$$



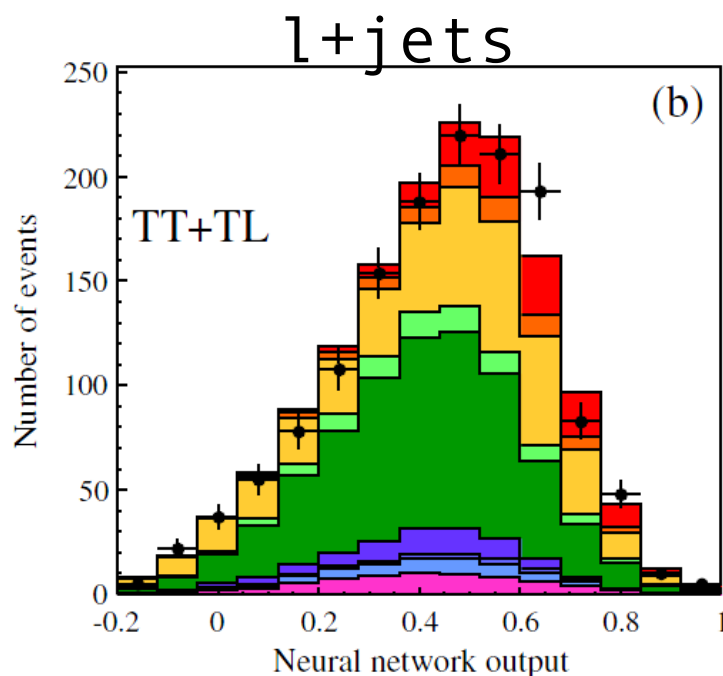
arXiv:1410.4909
submitted to PRL



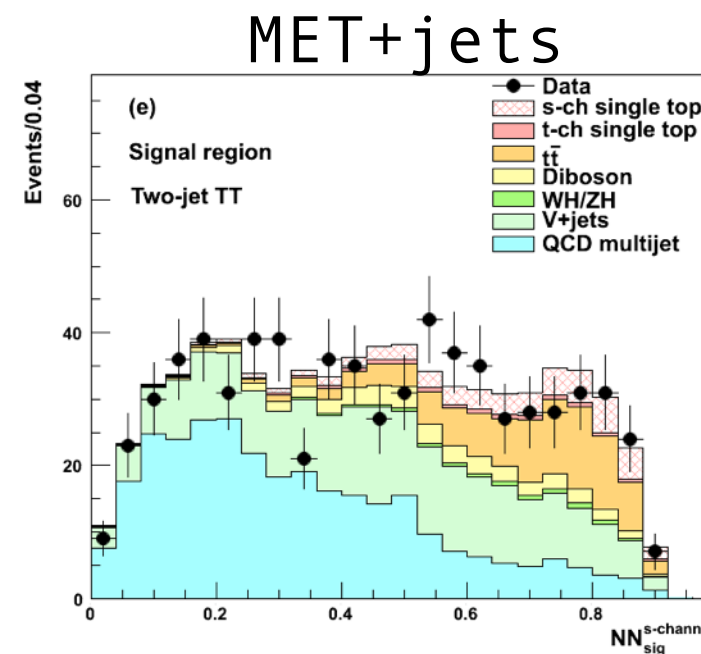
CDF s-channel Analyses

s-channel l+jets & MET+jets with full CDF dataset 9.5 fb⁻¹

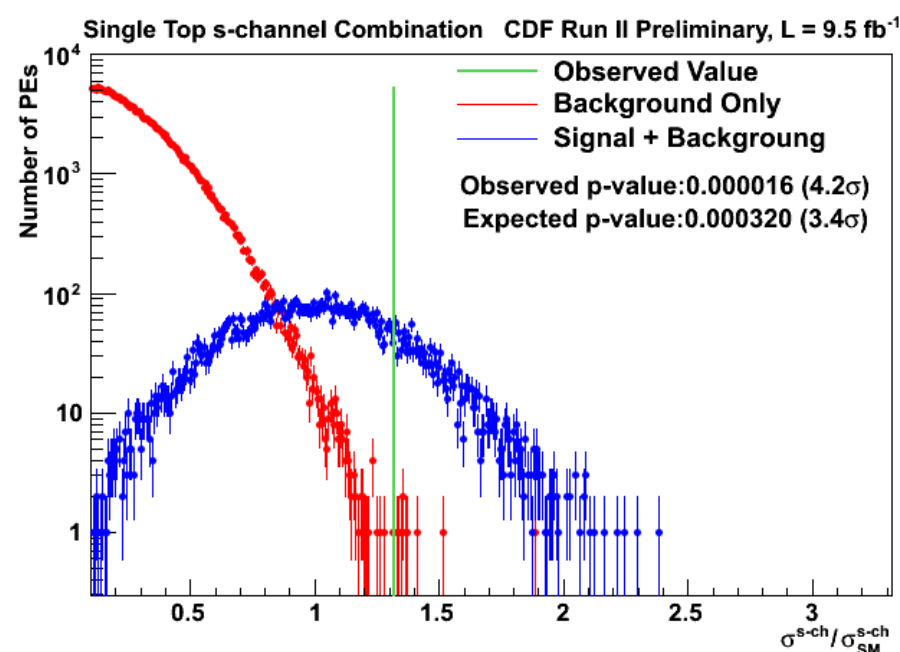
- l+jets and MET+jets s-channel optimized analyses based on Higgs search techniques and selection
- Both use MVA discriminant sensitive to s-channel only



PRL 112 231804
(2014)



PRL 112 231805
(2014)



$$\sigma_s = 1.36^{+0.37}_{-0.32} \text{ (stat+syst) pb} \\ (\pm 27\%)$$

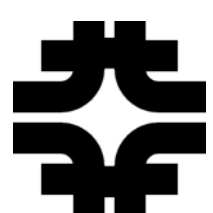
PRL 112 231805 (2014)

CDF s-ch Combination

4.2σ significance

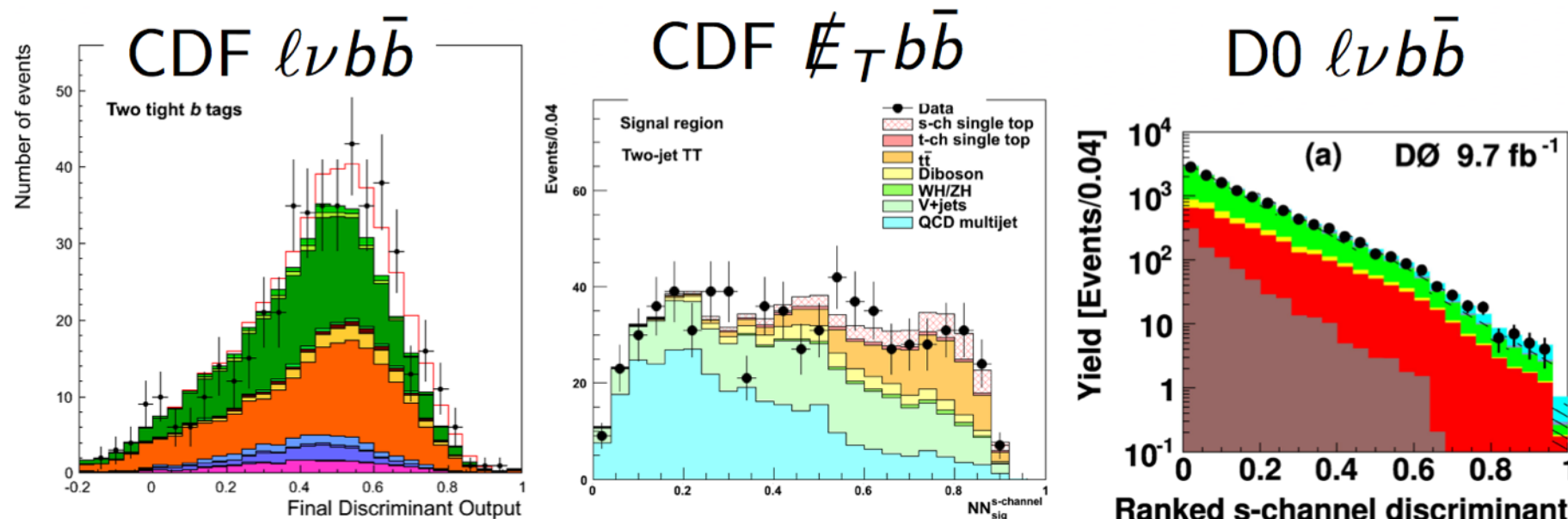


Tevatron Single Top Combinations



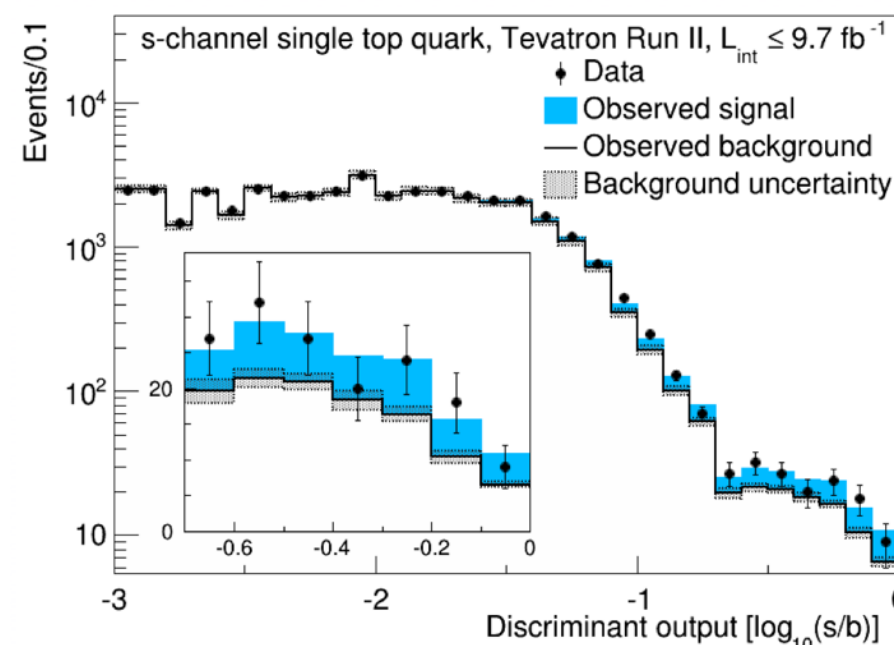
Tevatron s -channel Combination

Inputs



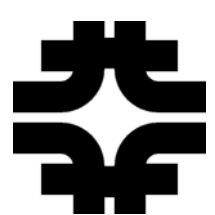
Output

- $L = 9.7 \text{ fb}^{-1}$
- Combine CDF (l+jets and MET+jets) & D0 discriminants (l+jets)
- Extract combined cross section using Bayesian statistical analysis



- Include all systematic uncertainties and takes in account correlations

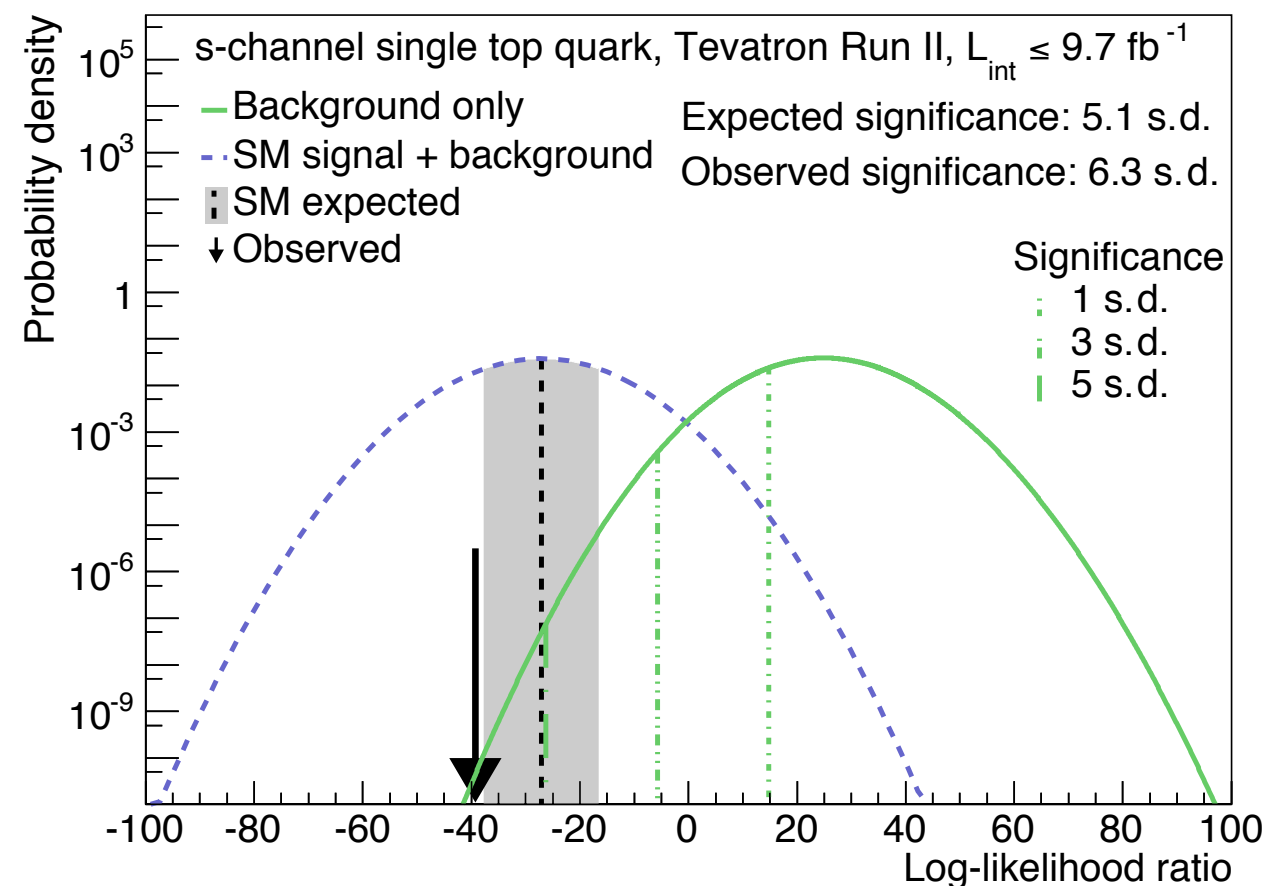
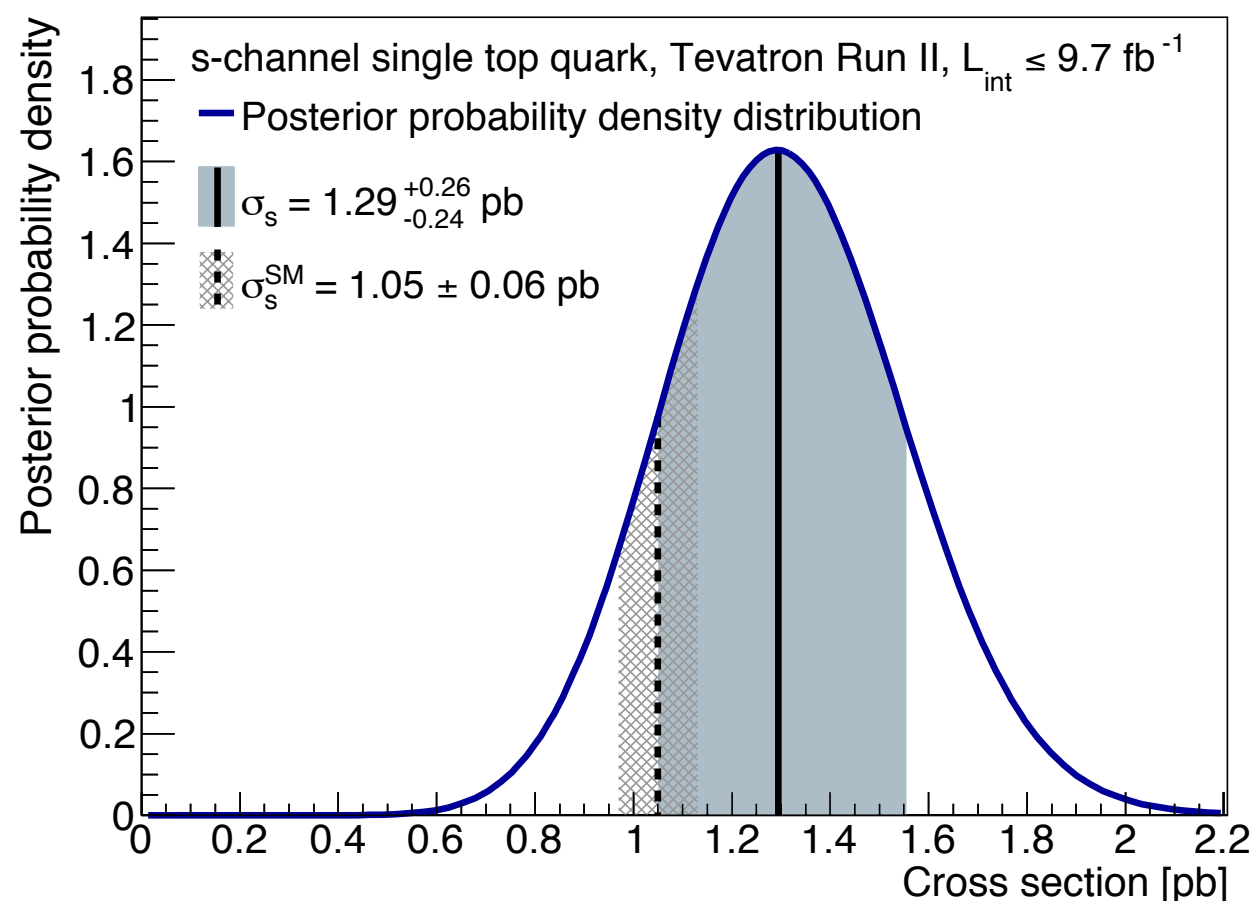
PRL 112 231803 (2014)



Tevatron *s*-channel Observation

$$\sigma_s = 1.29^{+0.26}_{-0.24} \text{ (stat+syst) pb } (\pm 19\%)$$

**P-value: $1.8 \times 10^{-10} \rightarrow 6.3\sigma$ observed significance
(5.1σ expected)**



First observation of *s*-channel single top production!

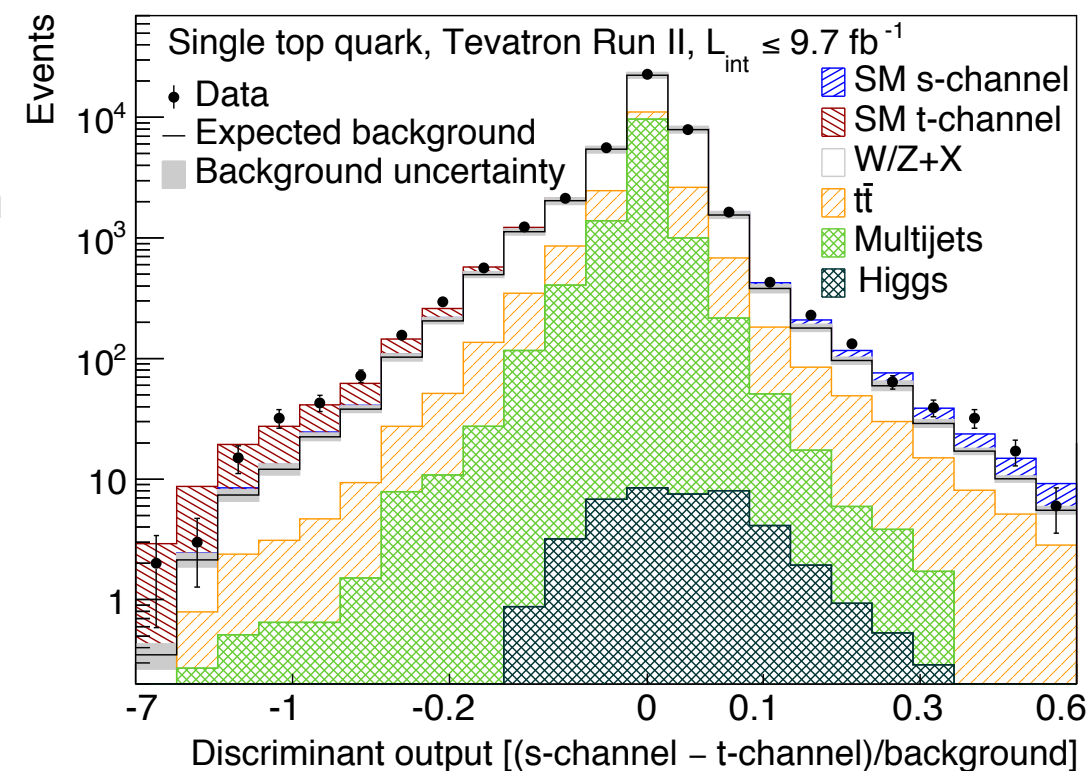
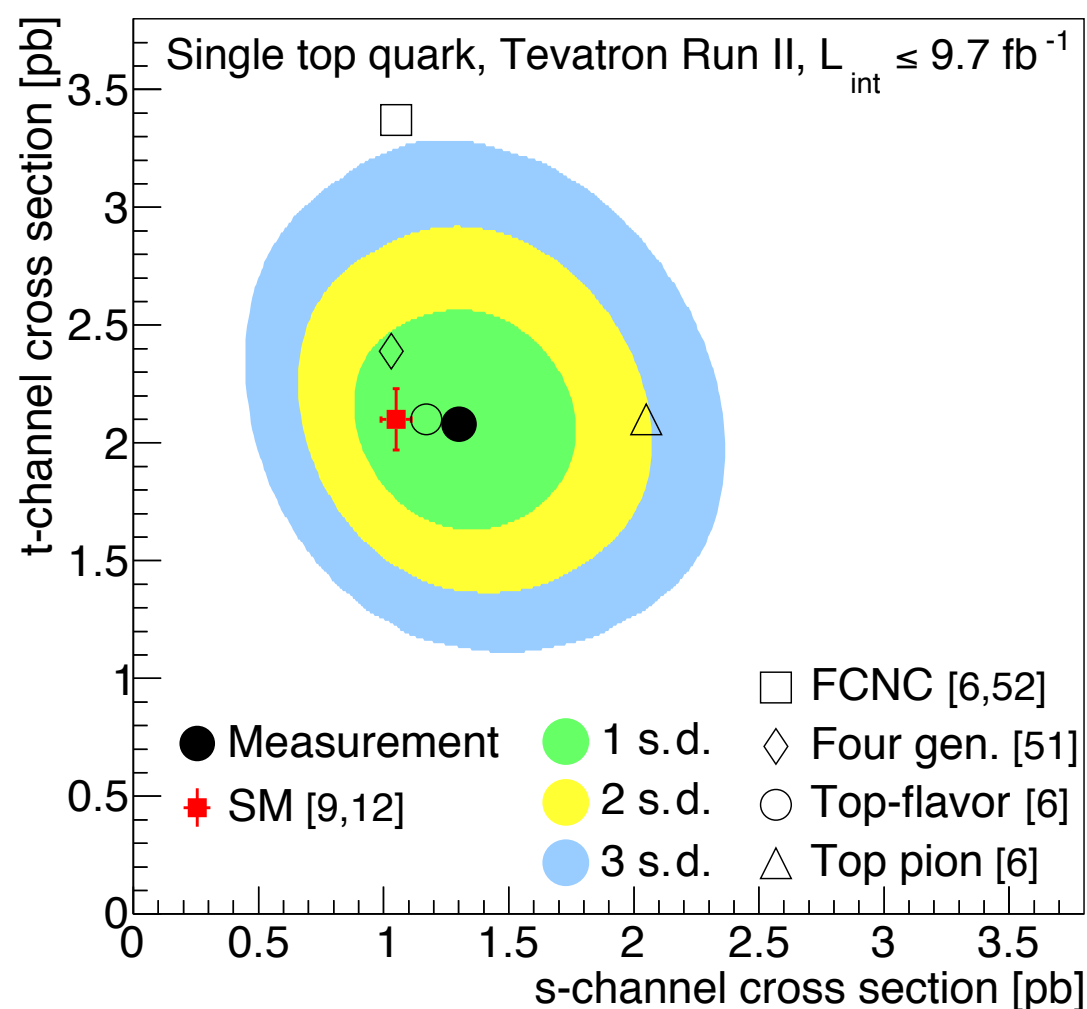
PRL 112 231803 (2014)



Tevatron $s+t$ Combination

Last Single Top legacy measurements from Tevatron!

- σ_{s+t} VS σ_t with $L < 9.7 \text{ fb}^{-1}$
- Combines CDF and D0 analysis: same method as s-ch
- Employ s-,t- channel discriminants from D0 and CDF
→ both fitted simultaneously
- σ_{s+t} obtained by integrating 2D posterior (σ_{s+t} vs σ_t) over σ_t with no assumption on SM σ_s / σ_t



$$\sigma_t = 2.25^{+0.29}_{-0.31} \text{ pb } (\pm 13\%)$$

$$\sigma_{s+t} = 3.30^{+0.52}_{-0.40} \text{ pb } (\pm 13\%)$$

arXiv:1503.05027
submitted to PRL



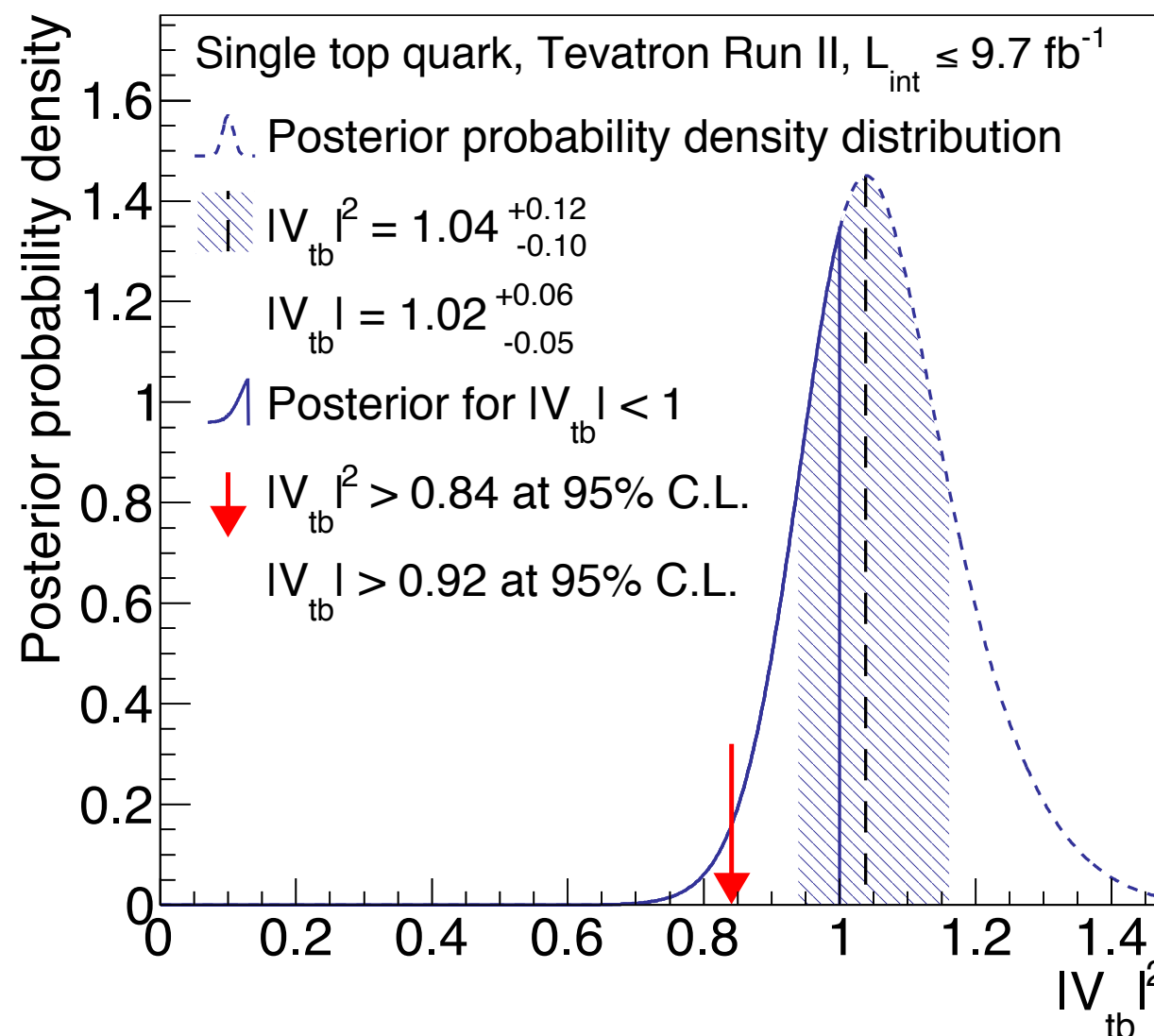
Tevatron $s+t$ Combination

$|V_{tb}|$ Matrix Element Extraction

- V_{tb} : same MVA discriminants as for s - and t -channel cross sections
- form a Bayesian posterior p.d. for $|V_{tb}|^2$ assuming a “flat” prior with no assumption on SM σ_s/σ_t

$|V_{tb}| > 0.92$ at 95% C.L.

**$|V_{tb}| = 1.02^{+0.06}_{-0.05}$
(5.4%)**



**arXiv:1503.05027
submitted to PRL**



Tevatron Single Top Summary

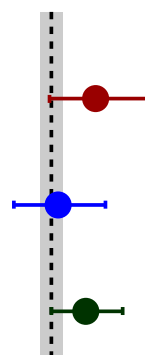
Tevatron Run II single top quark summary

Measurement

Cross section [pb]

s-channel:

CDF [25]



$1.36^{+0.37}_{-0.32}$

D0 [22]

$1.10^{+0.33}_{-0.31}$

29% first evidence: 3.7σ

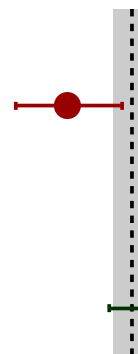
Tevatron [26]

$1.29^{+0.26}_{-0.24}$

19% first Observation: 6.1σ

t-channel:

CDF [21]



$1.65^{+0.38}_{-0.36}$

D0 [22]

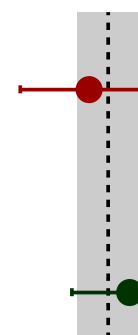
$3.07^{+0.54}_{-0.49}$

Tevatron [this paper]

$2.25^{+0.29}_{-0.31}$

s+t:

CDF [21]



$3.02^{+0.49}_{-0.48}$

D0 [22]

$4.11^{+0.60}_{-0.55}$

Tevatron [this paper]

$3.30^{+0.52}_{-0.40}$

13% ; $|V_{tb}|$: 5.3% precision

0 1 2 3 4
Cross section [pb]

--- Theory (NLO+NNLL) [9,12]

$m_t = 172.5 \text{ GeV}$

arXiv:1503.05027
submitted to PRL

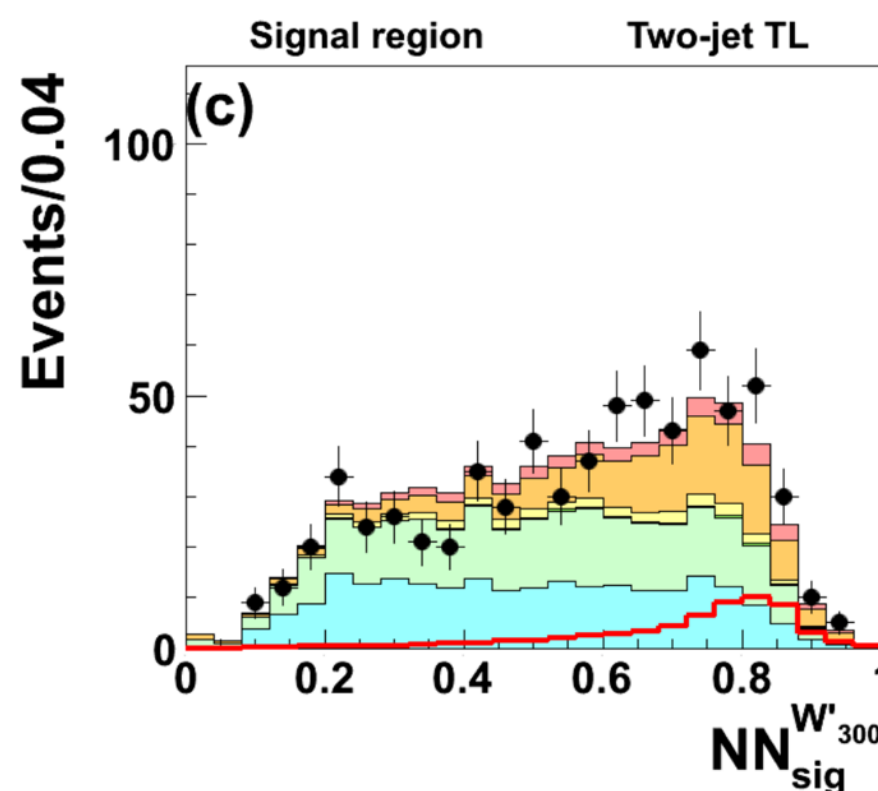
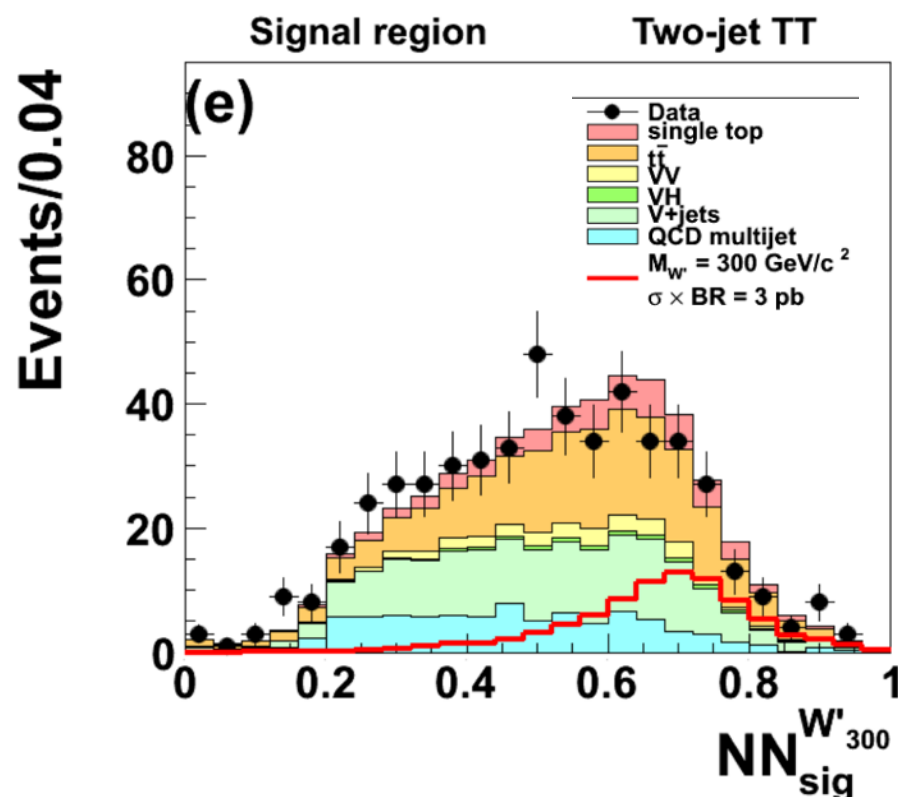
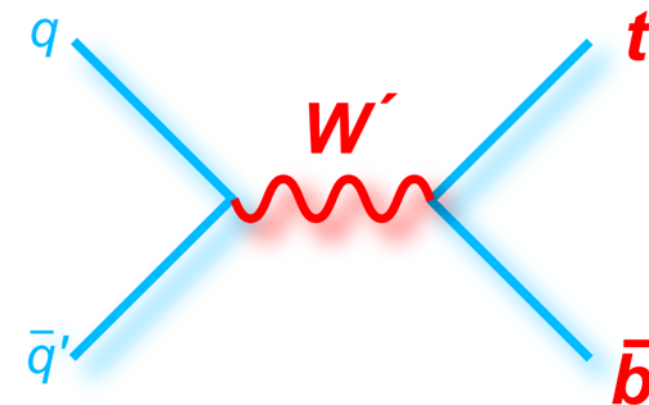
Full Tevatron
dataset
up to 9.7 fb^{-1}



Search for $W' \rightarrow tb$



- Several modifications of SM predict the existence of massive, shortlived states decaying to pairs of SM leptons or quarks.
 - Same topology as single top s-channel can be studied to search for W' boson
- Search is conducted with MET-based trigger requiring or not presence of a charged lepton in final state
- Signal modeled with **PYTHIA**: W' with $300 \leq M_{W'} \leq 900 \text{ GeV}/c^2$
- Dominant background: QCD rejected with NN_{QCD}
- Subsamples: #jets and #b-tags (2J1T...3J2T) and type of tag (T,L)



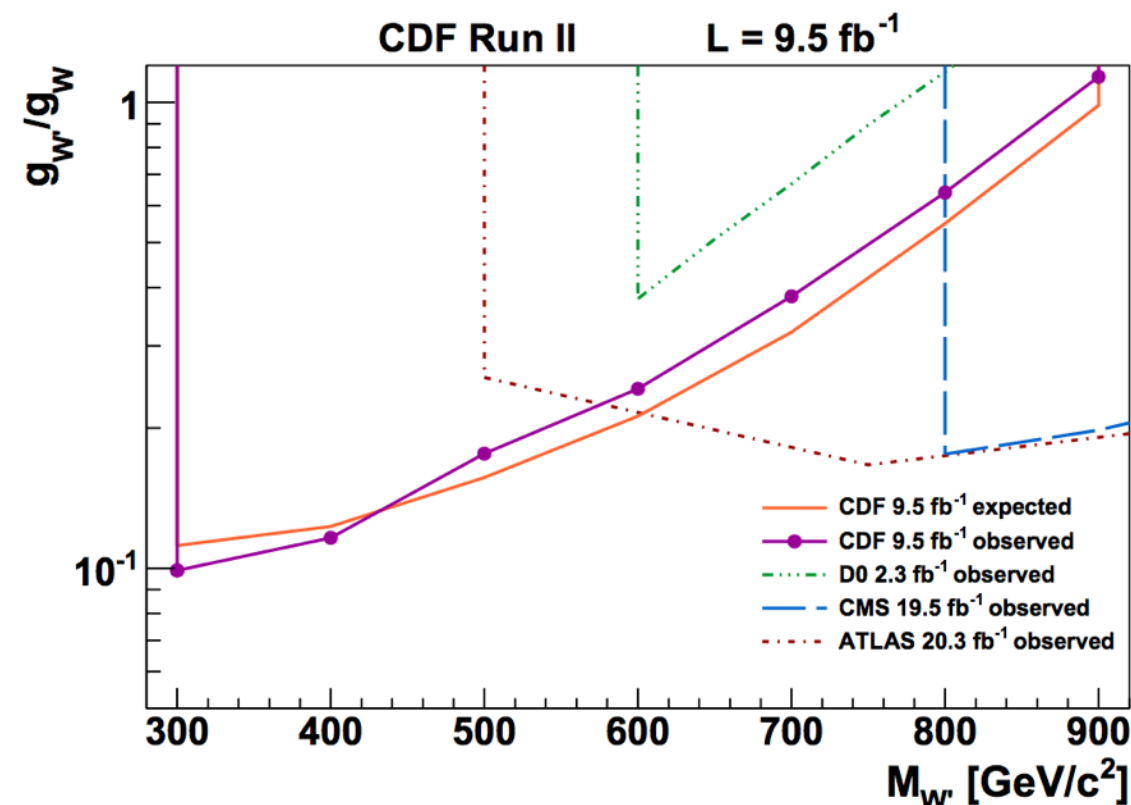
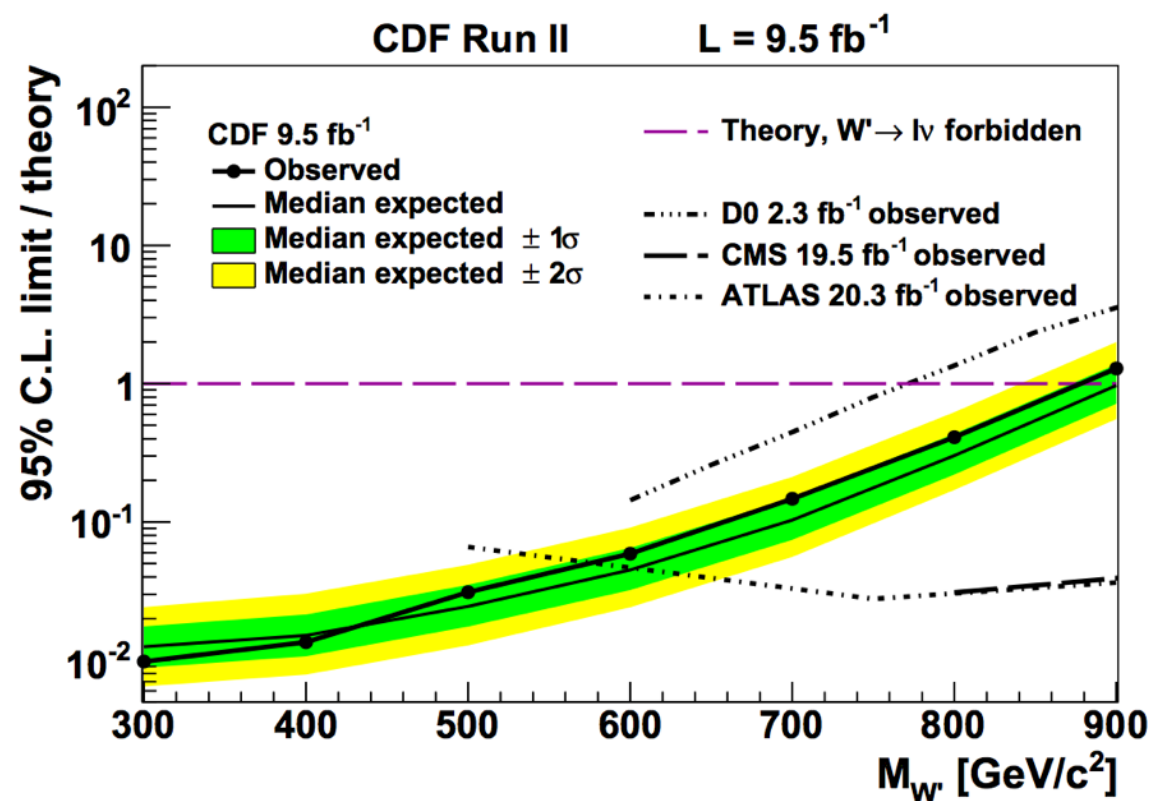
arXiv:1504.01536
accepted by PRL



Search for $W' \rightarrow tb$



- left-right symmetric BSM model with W' bosons of unknown mass and SM weak-coupling to fermions, is used as a benchmark model.
- Considering allowed and forbidden $W' \rightarrow tb$ decay to leptons
- Best exclusion limit for $M_{W'} \leq 600 \text{ GeV}/c^2$!



**W' excluded up to 860 (880) GeV/c^2 ,
for allowed (forbidden) lepton decay modes**

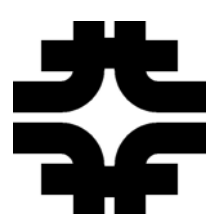
**arXiv:1504.01536
accepted by PRL**



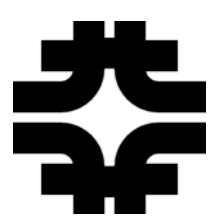
Summary

- Single Top was observed at CDF&D0 in 2009
- Now, Single Top program at Tevatron is complete!
 - ✓ All measurements in agreement with SM prediction!
 - ✓ At least for single top cross section, this is the final measurement by Tevatron!
- s-channel was the last missing block in ST: **Observed!**
- s+t final Tevatron combination has been performed
- BSM result in single top area presented!

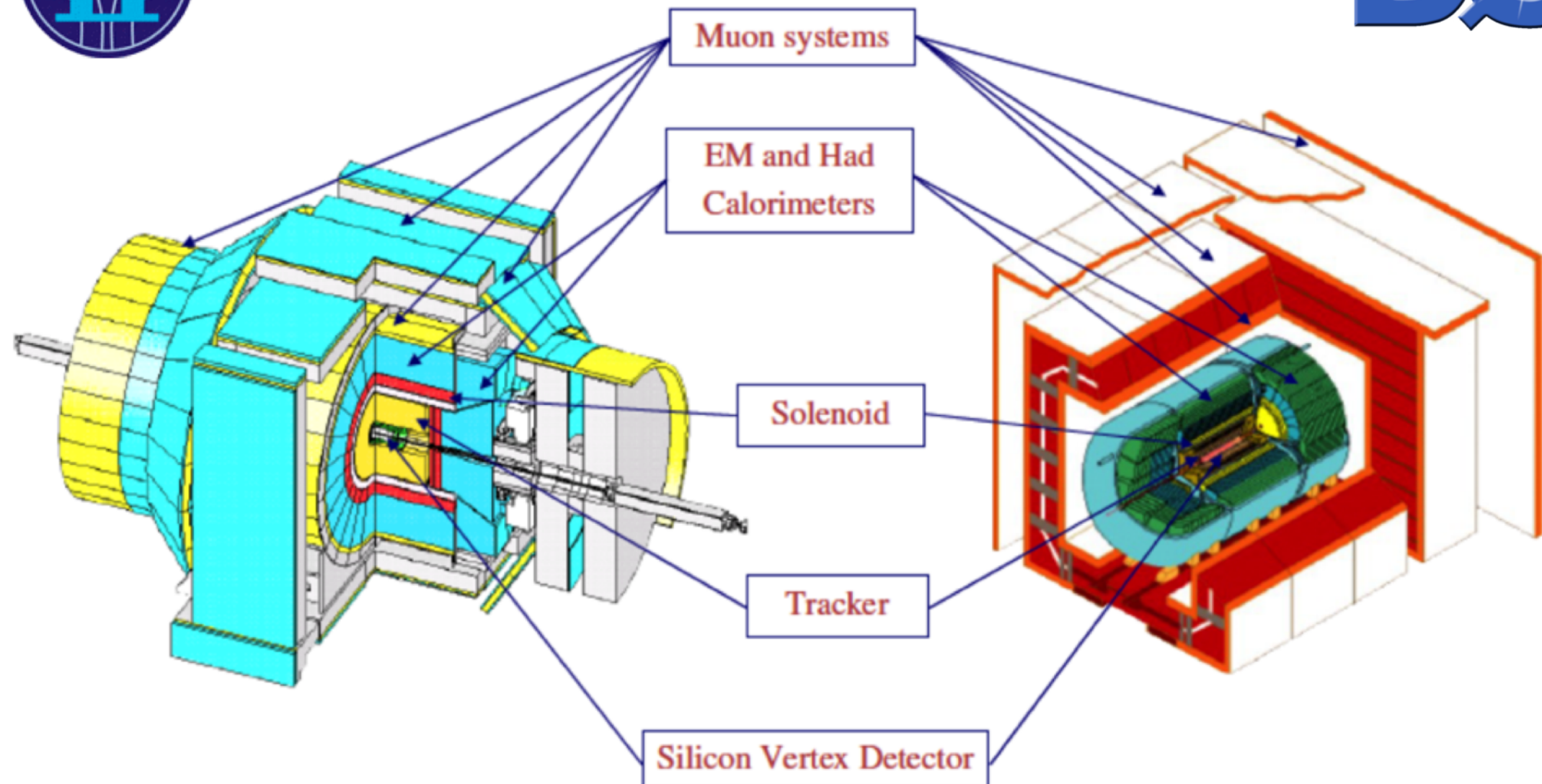
Thanks for the attention!



Backup



CDF and DØ detectors





Signal and Background Modeling

Electroweak/Top: Single Top, ttbar, diboson

- modeled by Monte Carlo (MC)
 - single top: **POWHEG** (CDF), **COMPHEP** (DØ)
 - ttbar: **PYTHIA** (CDF), **ALPGEN** (DØ)
 - diboson, WH: **PYTHIA**
- normalized to theoretical cross section

W+jets:

- modeled by **ALPGEN+PYTHIA** Monte Carlo (MC)
- normalisation and flavour composition from data

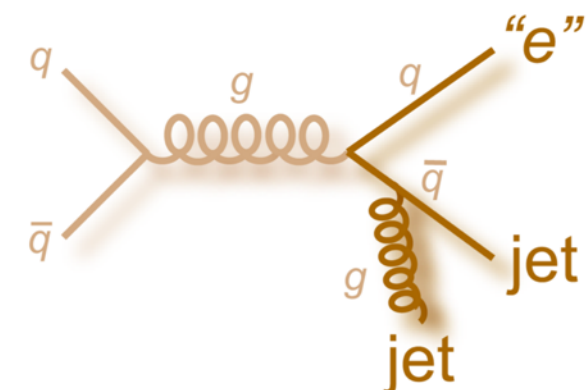
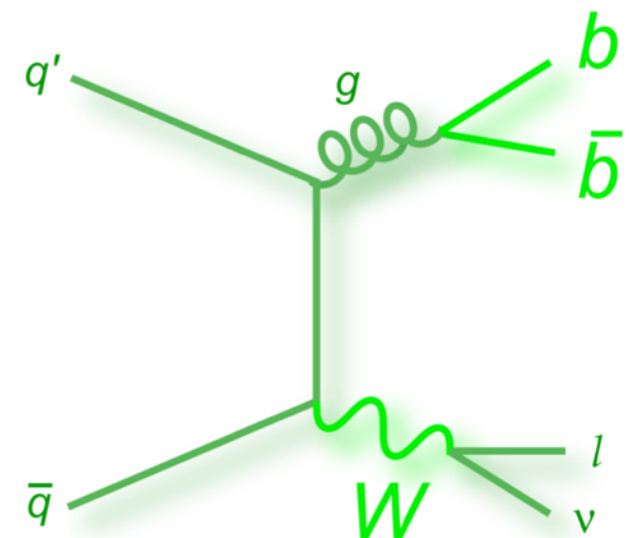
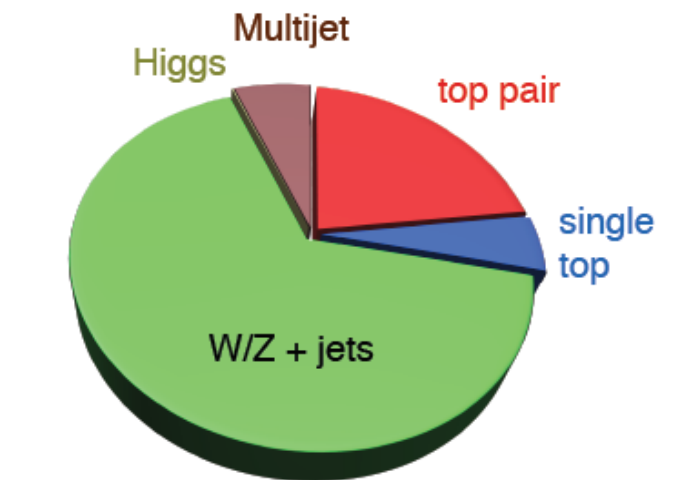
Mistags:

- falsely tagged light quark or gluon jet
- mistag probability from data

Z+jets: modeled by **ALPGEN+PYTHIA** MC

Multijet:

- Normalisation and shape from data-driven model





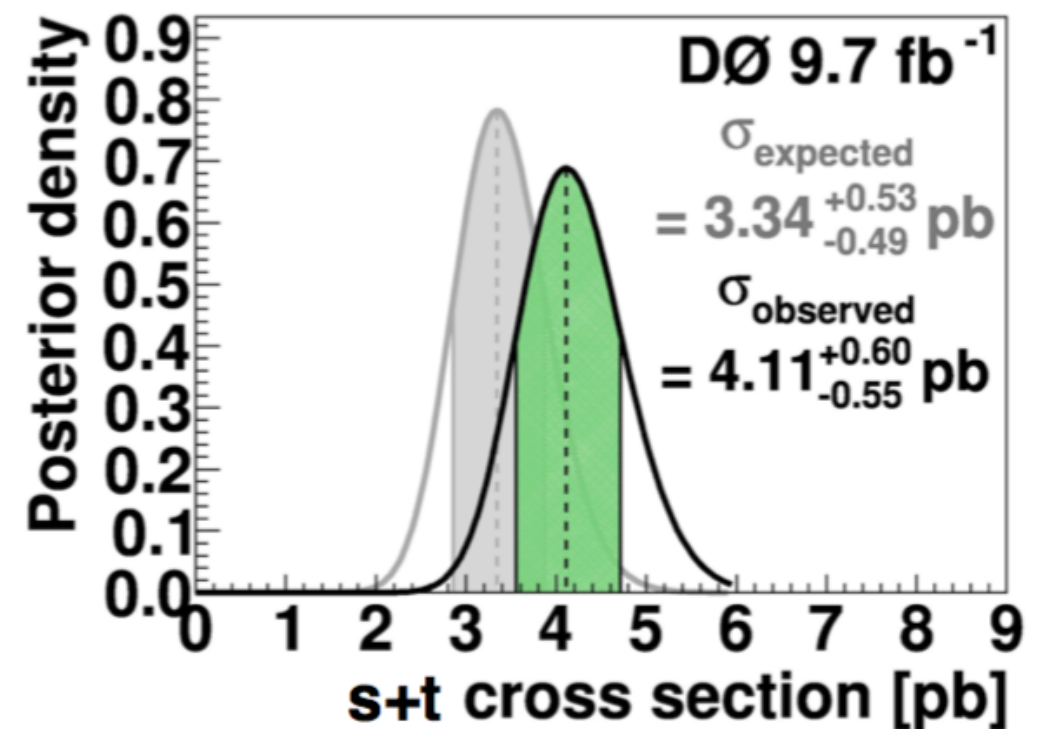
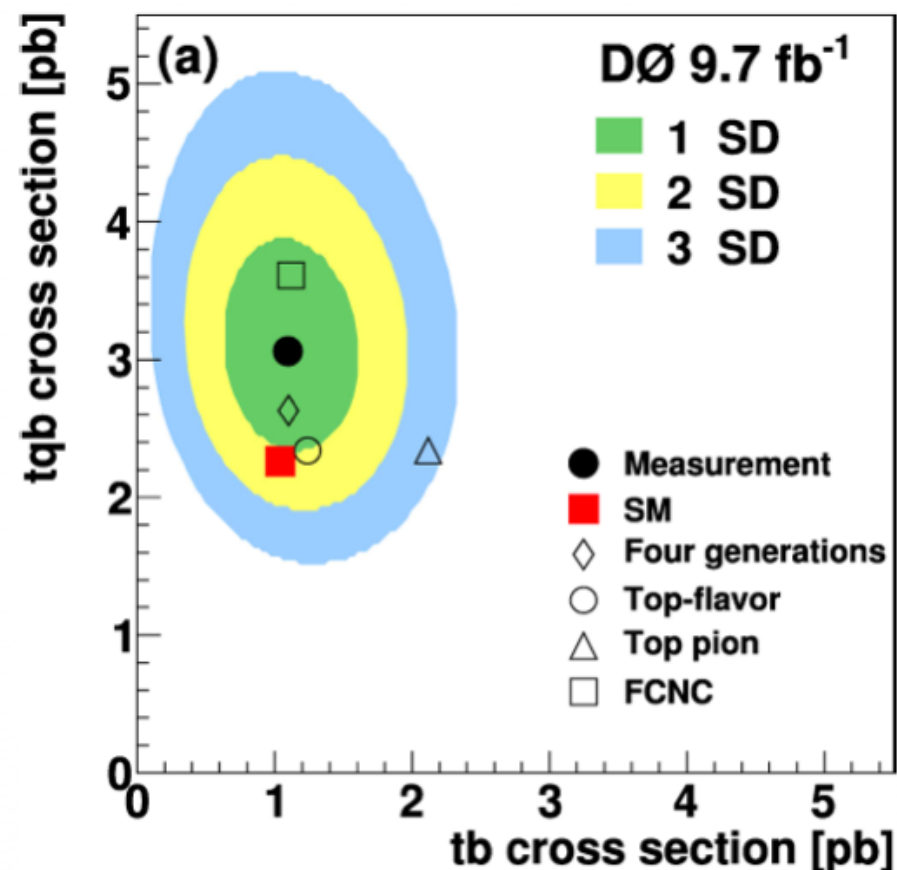
$D\bar{D}$ Single Top Analysis

$s+t$ cross section

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- 1D posterior obtained for σ_{s+t} integrating over σ_t with no assumption on SM σ_s/σ_t

$$\sigma_{s+t} = 4.11^{+0.60}_{-0.55} \text{ pb } (\pm 14\%)$$

$$|V_{tb}| > 0.92 \text{ at } 95\% \text{ CL}$$



s -ch VS t -ch cross section

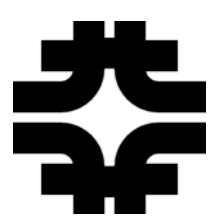
- 2D final discriminant sensitive to s -, t -ch
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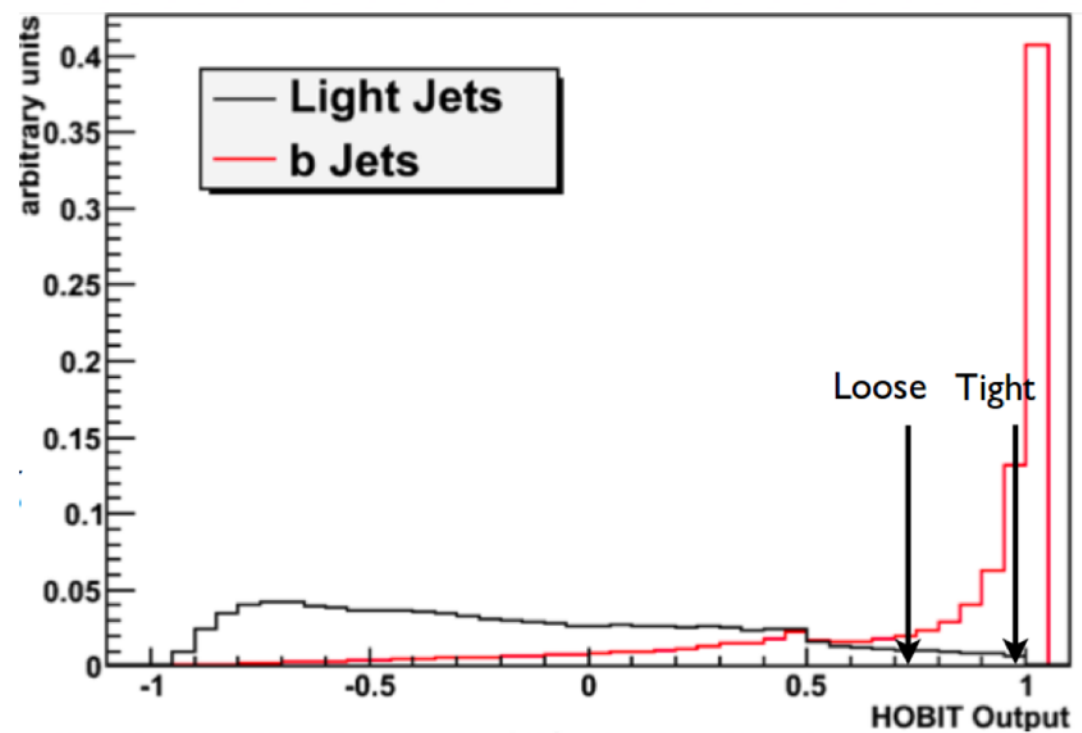
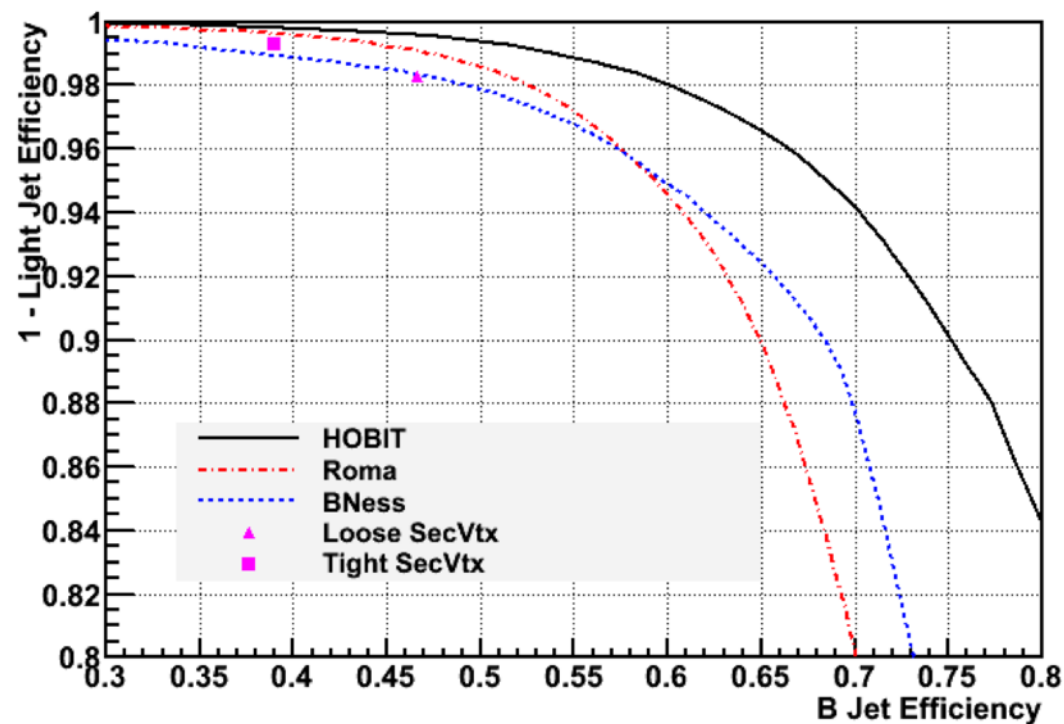
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first evidence with
 3.7σ significance

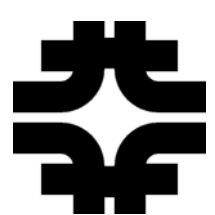
PLB 726, 656 (2013)



Hobit b-tagger at CDF



- A new b-jet identification algorithm optimized for $H \rightarrow bb$ searches: HOBIT
- Two different HOBIT cuts are used: tight b-tag (T), loose b-tag (L)



CDF $lvb\bar{b}$ $s+t$ Analysis

Strategy

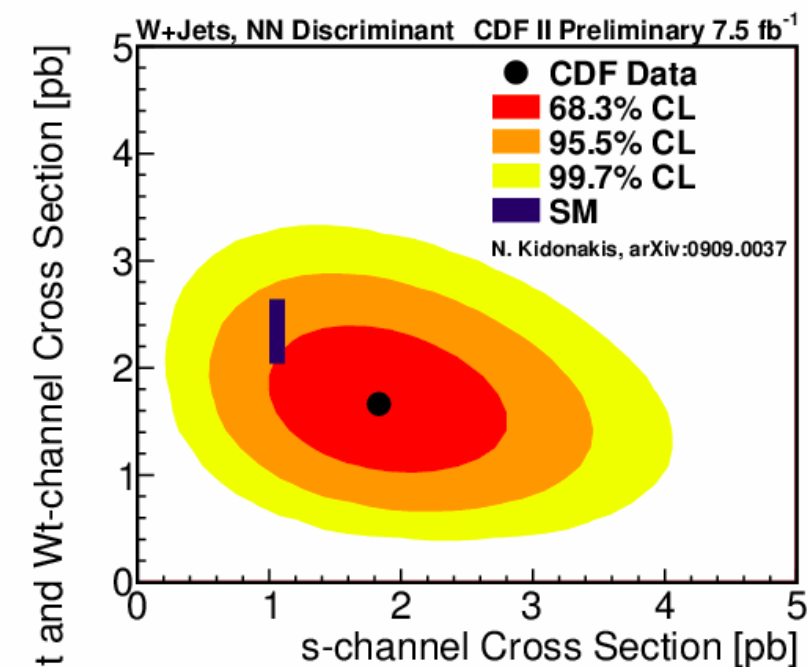
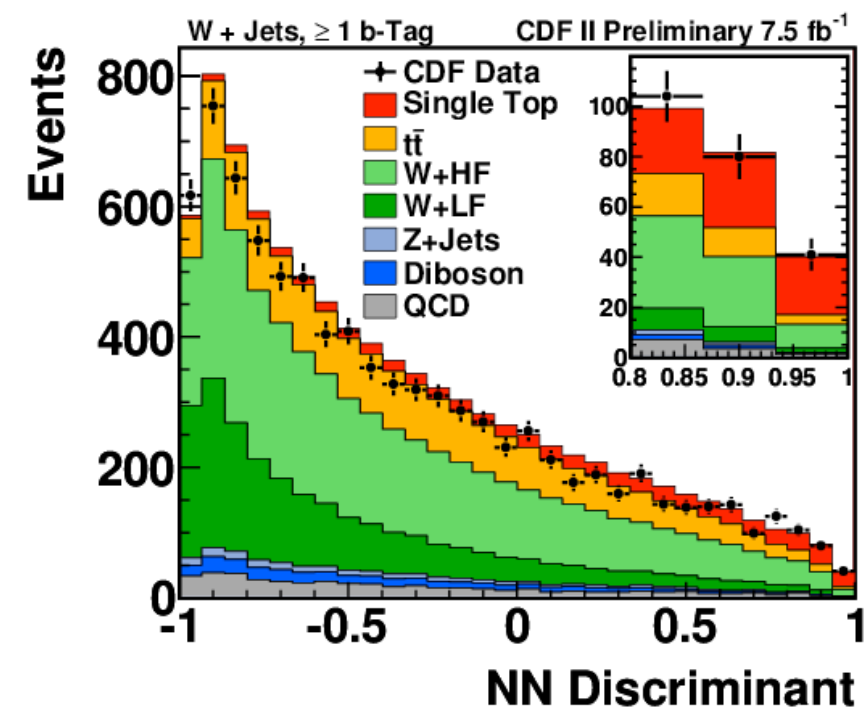
- Lepton+jets with 7.5 fb^{-1} of CDF data
- NNs trained with 11-14 variables
 - Use s-ch as signal in only 2J2T and t-ch for the rest
- Validate data-bg agreement in 0T Control Region
- Use admixture of systematics shifted samples
 - ➔ 3% improvement

Single Top $s+t+Wt$ Cross Section

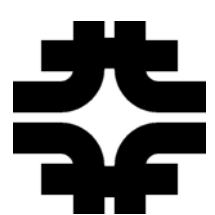
- maximum likelihood fit to the binned NN output
- Integrate the posterior probability density over the parameters associated with all sources of systematic uncertainties
- First inclusive measurement with Wt -ch at CDF!

$$\sigma_{s+t+Wt} = 3.04^{+0.57}_{-0.53} \text{ (stat+syst) pb } (\pm 19\%)$$

$$\sigma_s = 1.81^{+0.63}_{-0.58} \text{ pb}$$
$$\sigma_{(t+Wt)} = 1.66^{+0.53}_{-0.47} \text{ pb}$$



PRL 113, 261804 (2014)



CDF $\cancel{E}_T b\bar{b}$ $s+t$ Analysis

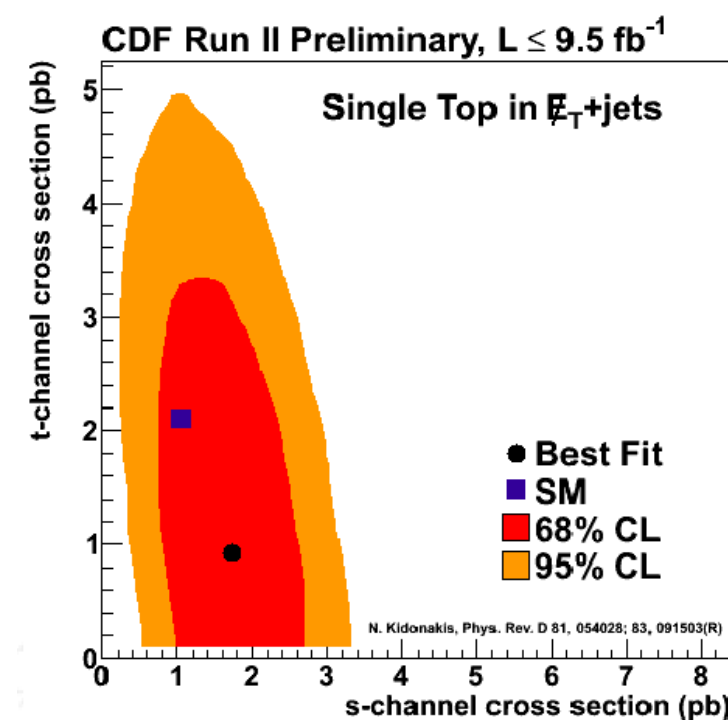
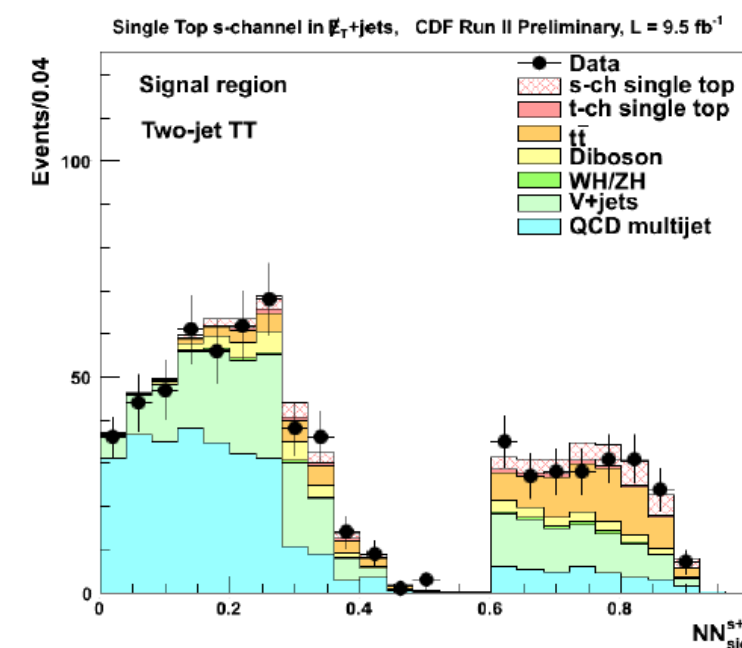
Strategy

- MET+jets with full CDF dataset 9.5 fb^{-1}
- Completely orthogonal dataset to ℓ +jets selection
- Subsamples wrt #jets and #b-tags (2J1T...3J2T)
 - CDF HOBIT multivariate tagger used
- Dedicated NN used to discriminate QCD, V+jets and $t\bar{t}$ for s-ch and t-ch
- 1D posterior obtained for σ_{s+t} assuming constant SM σ_s/σ_t

Results

$$\sigma_{s+t} = 3.53^{+1.25}_{-1.16} \text{ pb (stat+syst)} (\pm 34\%)$$

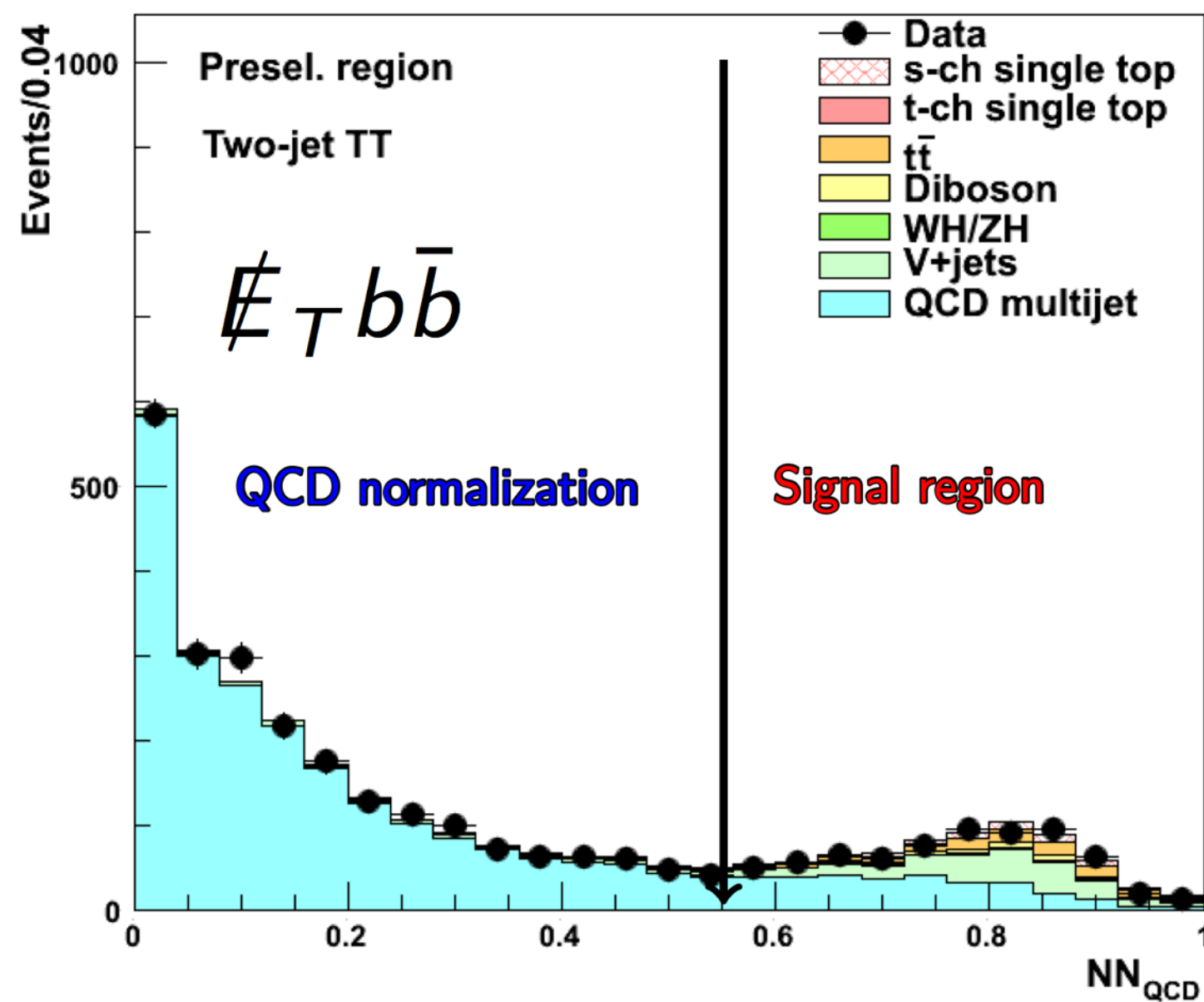
$$|V_{tb}| > 0.63 \text{ at 95\% CL}$$

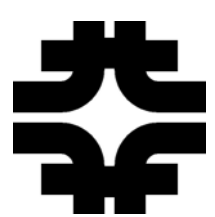


arXiv:1410.4909
submitted to PRL



$\cancel{E}_T + \text{jets}$ QCD rejection (CDF)

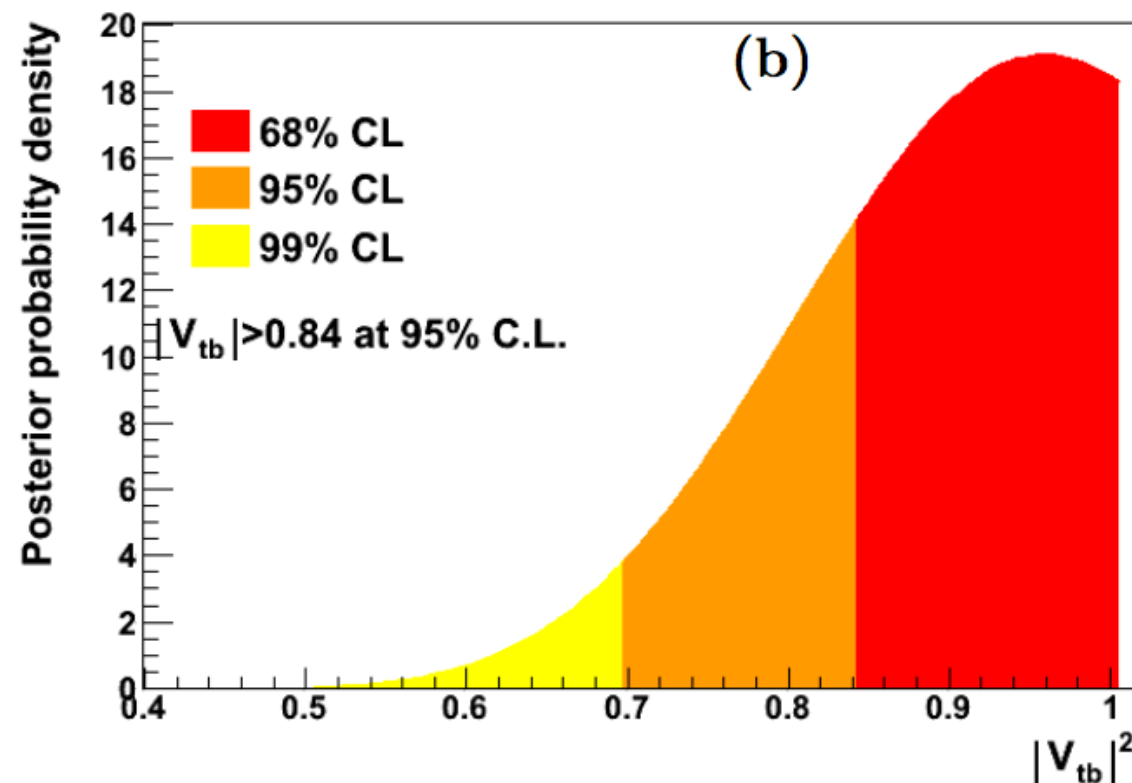




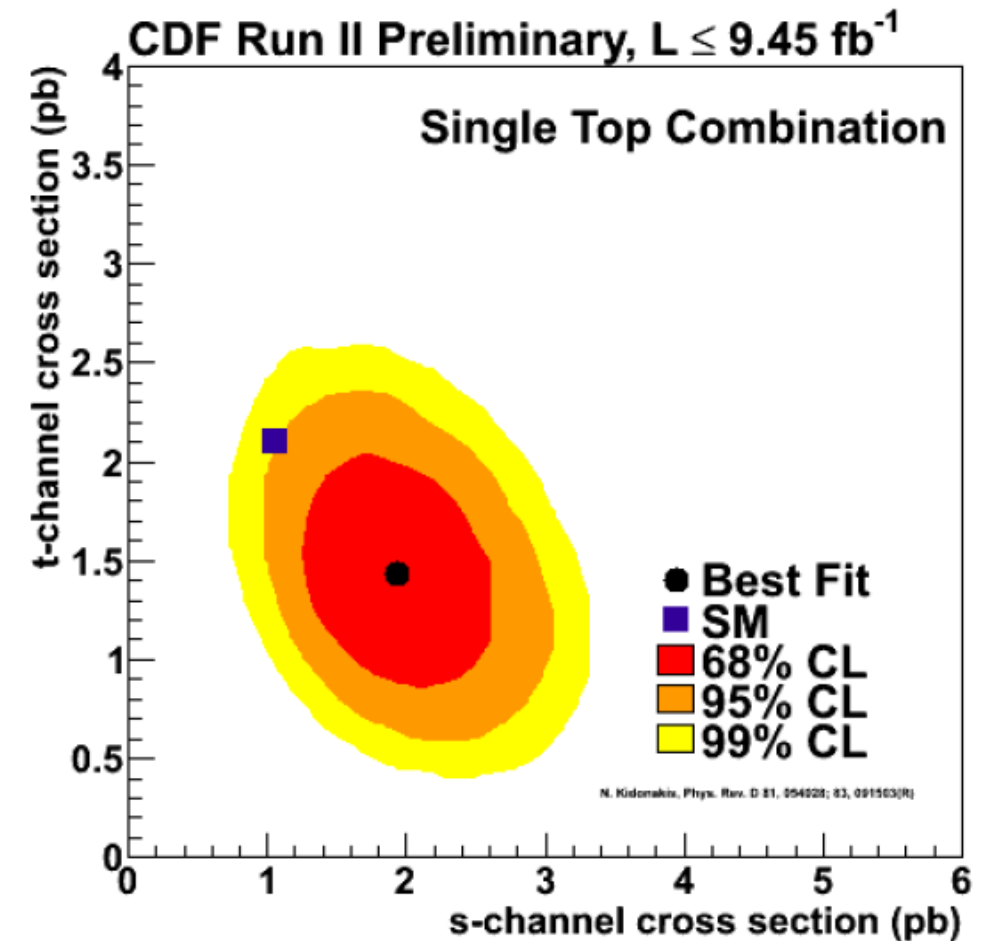
CDF $s+t$ Analyses

The results of the two $s+t$ analyses ($l+jets$ and MET +jets) are combined by taking the product of their likelihoods and simultaneously varying correlated uncertainties

$$\sigma_{s+t} = 3.02^{+0.49}_{-0.48} \text{ pb } (\pm 16\%)$$



$$|V_{tb}| > 0.84 \text{ at } 95\% \text{ C.L.}$$



CDF note 11033



Uncertainties

Systematic uncertainty	CDF		D0		Corre- lated
	Norm	Dist	Norm	Dist	
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	●	3–8%		Yes
Background (simulation)	2–12%	●	2–11%	●	Yes
Background (data)	15–40%	●	19–50%	●	No
Detector modeling	2–10%	●	1–5%	●	No
<i>b</i> -jet-tagging	10–30%		15–40%	●	No
JES	0–20%	●	9–40%	●	No

s–ch Observation

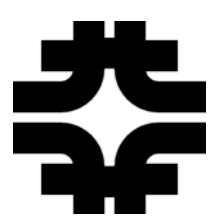
total expected uncertainty: 20%

expected uncertainty w/o systematics: 14%

s+t Tevatron

total expected uncertainty: 13%

expected uncertainty w/o systematics: 8%



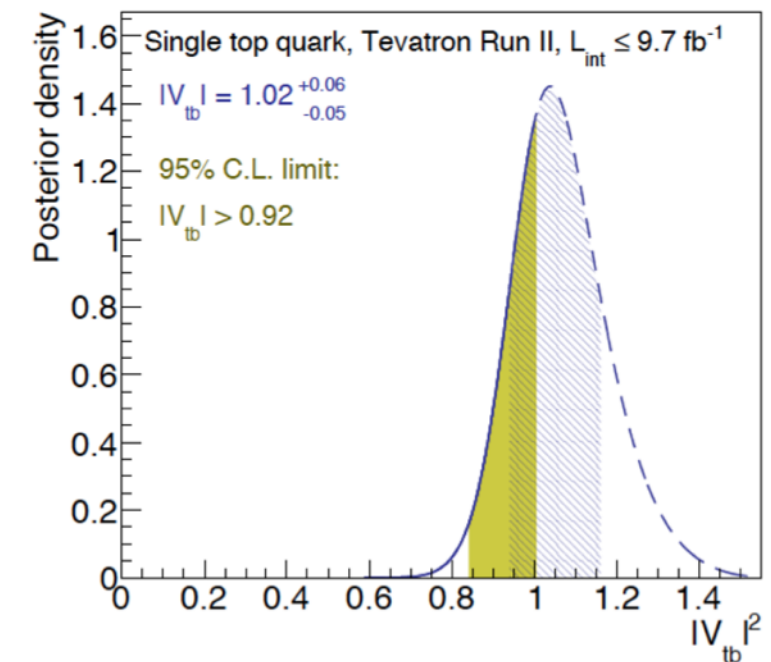
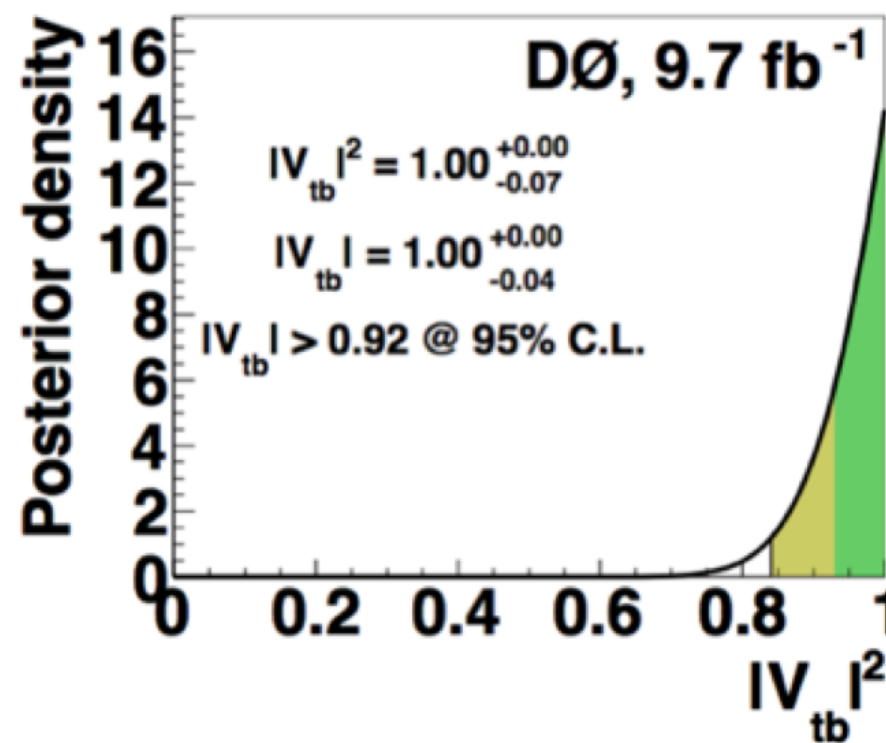
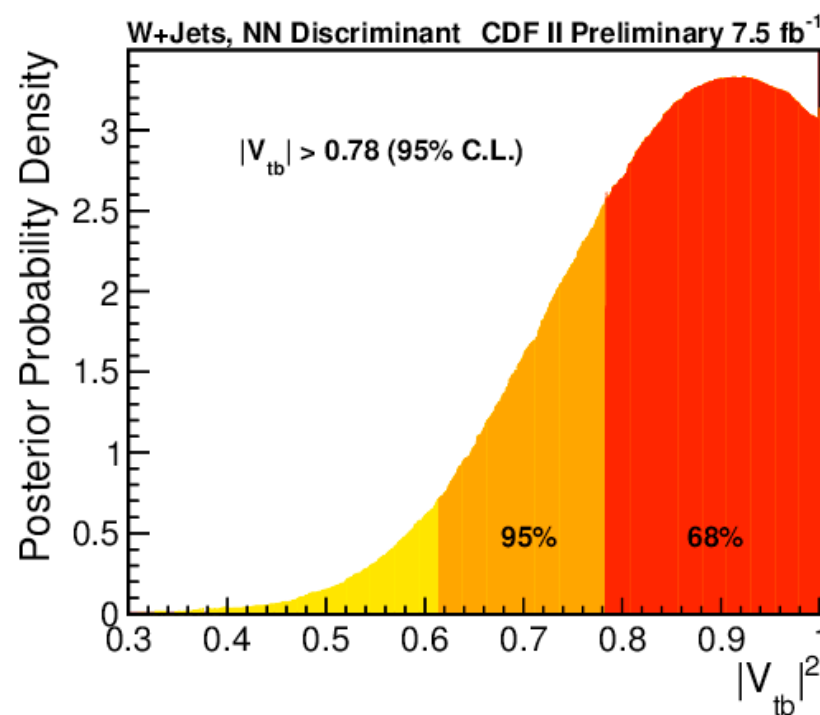
$|V_{tb}|$ Measurement

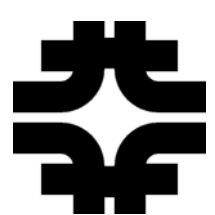
- $\sigma(s+t+Wt) \propto |V_{tb}|^2$ so we can extract the matrix element, assuming:

- SM top quark decay: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- V-A and CP conserving Wtb vertex
- No assumption on # of families or CKM unitarity

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \boxed{V_{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- additional systematic uncertainties: theoretical uncertainty on single top cross section





Tevatron $s+t$ Combination & BSM

